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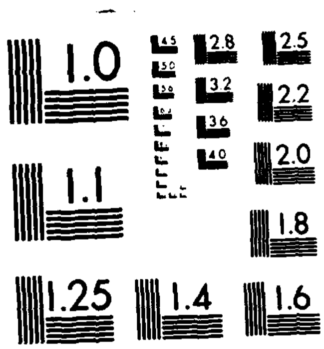

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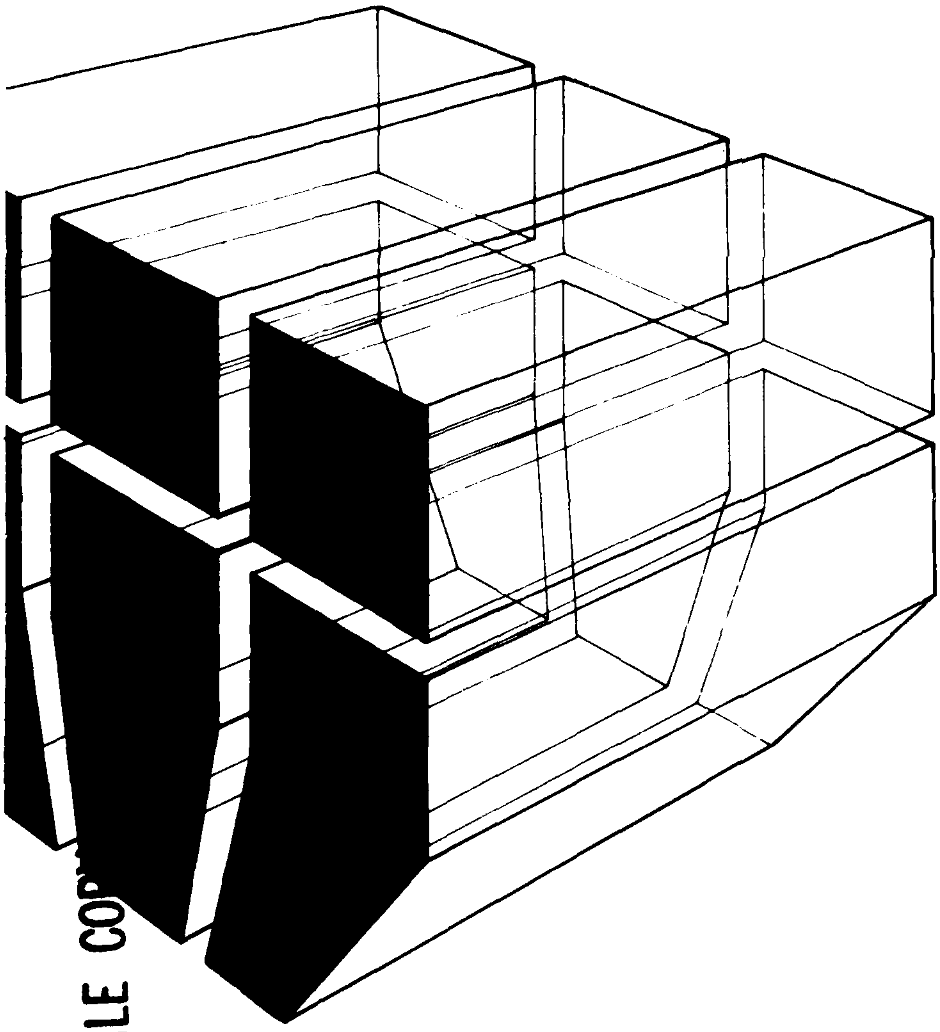
TECHNICAL REPORT M-326
January 1983

EFFECTS OF HIGH HEAT INPUT WELDING OF CONSTRUCTION STEELS A36, A514, AND A516



by
R. Weber

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This report documents the results of a study of shielded metal-arc welding (SMAW) and gas metal-arc welding (GMAW) butt weld tests using high heat inputs of 60 to 90 kJ/in. (2362 to 3543 J/mm). The steels used in this study were American Society for Testing and Materials (ASTM) Specifications A36, A514, and A516. Plate thicknesses were 3/4 to 1 in. (19 to 25 mm).

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It was concluded that strength levels were generally reduced by the higher heat inputs, but impact properties were not affected. A table of recommended heat inputs for the steels and electrodes investigated during this study is given.

FOREWORD

This investigation was performed for the Directorate of Engineering and Construction, Office of the Chief of Engineers (OCE) under Project 4A762731AT41, "Military Facilities Engineering Technology"; Task Area B, "Construction Management and Technology"; Work Unit 034, "Welding Criteria for Construction Based on Process Variables and Flaw Criticality." The OCE Technical Monitor is Mr. George Matsumura, DAEN-ECE-G.

This investigation was performed by the Engineering and Materials (EM) Division of the U.S. Army Construction Engineering Research Laboratory (CERL). Dr. R. Quattrone is Chief of CERL-EM.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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EFFECTS OF HIGH-HEAT INPUT WELDING OF CONSTRUCTION STEELS A35, A514, AND A516

1 INTRODUCTION

Background

In many structures built recently, the U.S. Army Corps of Engineers has taken advantage of some of the physical and mechanical property improvements of the American Society for Testing and Materials (ASTM) Specification A516 for carbon steel plate for moderate and lower temperature pressure vessels, and ASTM A514 for high-strength, low-alloy structural steel. However, adequate weldability safeguards are required when structures are built under special provisions for the use of higher-quality steels. Weld-related failures can include structural failures attributed to lamellar tearing of plates as a result of welding, failures of structural beams caused by misapplication of the shielded metal-arc welding (SMAW) process, and failures in high-temperature hot water distribution systems because of overstress caused by lack-of-penetration defects.

SMAW and gas metal-arc welding (GMAW) are the predominant forms of electric arc welding used today. SMAW is used about twice as often as GMAW for both field and shop fabrication. For many years, the only way to control these welding processes has been to limit the heat input (measured in Joules per linear inch of weld). Heat input is determined by using the simple relation:

$$\text{Heat input} = \frac{\text{voltage x current}}{\text{travel speed}}$$

The heat input limit was generally set to a maximum of 55 kJ/in. (2165 J/mm).

The U.S. Army Construction Engineering Research Laboratory (CERL) has conducted a three-part research program to determine voltage, current, and travel speed limits for various plate steels and welding electrodes. In the first part of the study, the limits on voltage, current, and electrode travel speed were determined on the basis of bead-on-plate welds examined for quality.[1] The second part of the study refined these limits using their interrelationship with nugget area and heat input based on butt weld mechanical properties. This work concentrated on the limits for SMAW and GMAW electrodes combined with a carbon steel (A36), a pressure-vessel steel (A516), and a high-strength, low-alloy steel (A514).[2] The third part of the study refined these limits by looking at the effects of high restraint on the weld joint and the effects on mechanical properties as well as the problem of cracking in the weld joint under the influence of high restraint.[3] This report documents additional data from SMAW and GMAW butt weld tests using high-heat inputs of 60 to 90 kJ/in. (2362 to 3543 J/mm).

CERL's earlier work mainly used welding heat inputs in the low-to-moderate range (less than 60 kJ/in. [2362 J/mm]). That research suggested limits on the heat input to insure the quality and strength levels of the deposited weld metal using plates 3/4- and 1-in. (19- and 25-mm) thick to represent the greatest thickness found in typical Corps of Engineers construction.

Those limits, set for the low ends of the heat input range, were based on the operating and handling characteristics of the electrode and the quality of the weld metal. The upper limits were set based on the mechanical properties of the weld and its heat-affected zone (HAZ). In many cases, the upper limits were tentative because there were no data for high heat input weldments. The strength levels, particularly the yield strength, tended to decrease as the heat input increased. Lines were projected to show where the upper limit would be.

The series of welds described in this report were made in the same three types of steel used in the previous studies (ASTM A36, A514, and A516), using the same two welding processes (SMAW and GMAW). The weldments were then examined to determine the upper limits of the heat input.

Objective

The objective of the portion of the study reported here was to determine the high heat input limits necessary to ensure proper weld strength levels for construction steels.

[1] R. A. Weber, *Determination of Arc Voltage, Amperage, and Travel Speed Limits by Bead-on-Plate Welding*, Technical Report M-197/ADA033684 (U.S. Army Construction Engineering Research Laboratory [CERL], December 1976).

[2] R. A. Weber, *Determination of the Effect of Current and Travel Speed of Gas Metal-Arc Welding on the Mechnical Properties of A36, A516, and A514 Steels*, Technical Report M-278/ADA085342 (CERL, May 1980).

[3] R. A. Weber, *Weldability Characteristics of Construction Steels A36, A514, and A516*, Technical Report M-302/ADA111866 (CERL, December 1981).

Mode of Technology Transfer

The information in this report is part of a research effort designed to maintain Corps of Engineers Guide Specification (CEGS) 05141 *Welding, Structural;* CEGS 15116, *Welding, Mechanical;* and Army Technical Manual (TM) 5-805-7, *Welding: Design, Procedures, and Inspection.*

2 APPROACH

CERL achieved the objective of this study by defining the upper limits of heat input by testing the tensile and impact strength of joint welds produced with manual SMAW and automatic GMAW in carbon steel (A36), pressure-vessel steel (A516), and high-strength, low-alloy steel (A514).

Materials

Table 1 lists the plate steels (by ASTM code numbers) and the electrodes (by AWS code numbers) used in this investigation. Electrode types were selected for use with plate materials based on the AWS *Structural Welding Code* and the common usage for Corps of Engineers construction.[4] One type of plate steel was chosen from each of the three categories of steel used frequently in Corps construction:

1. Carbon steel (ASTM A36)

2. Pressure-vessel steel (ASTM A516)

3. High-strength, low-alloy steel (ASTM A514).

Table 2 lists the as-received tensile properties and the ASTM specification limits for each of the plate materials used in this investigation. Table 3 lists the AWS specification limits for the electrodes used to fabricate the high heat input weldments.

Experimental Procedure

The weld joint used in this investigation was a 60-degree included angle, single-V butt joint with a 1/8-in (3.2-mm) root opening with backing strap (Figure 1). The weld length was about 24 in. (610 mm). The completed test weldment was about 12 x 24 in. (305 x 610 mm). Each plate material required six weldments, a total of 18 weldments. All plate material was cut and leveled using an oxyacetylene cutting apparatus. The surfaces were then ground with an abrasive disk grinder to remove the oxides and slags from the weld joint area. Each completed weldment was nondestructively examined for soundness using X-ray radiography in accordance with MIL-R 11468. If the weldment had not met the specification, it would have been redone.

One macrospecimen, three tensile specimens, and 10 dynamic tear impact specimens were machined from each completed sound weldment. Figure 2 shows a schematic of specimen locations as machined from the weldments.

The impact specimens were machined so that half were notched in the weld metal and the other half were notched adjacent to the weld in the HAZ. They were tested at temperatures ranging from −40 to +60°C according to ASTM standards.[5]

Two of the tensile specimens were machined from the weld metal; the third was machined from the HAZ. All the tensile specimens were tested as ambient temperature according to Military Standard (MIL-STD) 418c.[6] The tensile test results included the yield strength, the ultimate tensile strength, the elongation, and the reduction in area.

The macrospecimens were polished and etched using Nitol etchant and visually examined for small flaws not shown by radiography.

Welding Procedure

Arc voltage, current, and travel speed for all specimens were selected based on the results of CERL's previous work. Table 4 shows the welding variables for all the weldments. The same joint design was used for each material type. The nonstandard joint was used to insure enough weld metal for all the tests. All welding was done using direct current with the electrode's positive terminal.

The heat inputs were targeted at 60, 75, and 90 kJ/in. (2362, 2952, and 3543 J/mm) for each process and material. The actual heat inputs are shown in Table 4.

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[4] *Structural Welding Code*, D1.1 (American Welding Society [AWS], 1982).

[5] *1982 Annual Book of ASTM Standards, Part 10, Metals Physical, Mechanical, Corrosion Testing*, Designation E604, "Standard Test Method for Dynamic Tear Energy of Metallic Materials," pp 709-717.

[6] *Mechanical Tests for Welded Joints*, Military Standard (MIL-STD) 418c (June 1972).

3 DATA ANALYSIS AND DISCUSSION

A36 Weldments

Tensile Test Results

Figure 3 is a photomacrograph of the macro-specimens from the SMAW and GMAW weldments. The cross sections in the figure show that the weld beads are made up of very coarse dendrites. The HAZ contains refined grain sizes and coarser grains. The heat of welding is sufficient to refine the coarse dendrites of the previous weld bead or cause grain growth in the already fine grains of the base metal. The GMAW beads penetrate deeper than the SMAW beads.

Table 5 and Figure 4 present the test results for the E7018 weld metal and the A36 HAZ specimens over the respective heat inputs. Table 6 and Figure 5 present the test results for the ER70S-3 weld metal and the A36 HAZ specimens over the respective heat inputs. The minimum yield strength and ultimate tensile strength are the same for both the GMAW and the SMAW welding electrodes: 60 ksi (413.7 MPa) minimum yield strength and 72 ksi (496.4 MPa) minimum tensile strength. At the highest heat input of the SMAW test, the tensile strength shows scattered results with one value below the minimum. The mechanical properties of the weld are otherwise satisfactory. On the other hand, the usability of the electrode falls off rather rapidly as the heat input increases. The two welds at 75 and 90 kJ/in. (2952 and 3543 J/mm) heat input were very difficult to fabricate because the slag was extremely fluid and difficult to control. Porosity was a continuous problem. The 60-kJ/in. (2362-J/mm) heat input weld weld had a marked reduction in tensile ductility because of porosity in the weld metal that affected the tensile test results. The other test specimens had relatively small amounts of porosity even though the weldment had porosity scattered through it.

The GMAW yield strength was at or below the minimum of 60 ksi (413.7 MPa). When compared to the previous data for this system, the yield strength had apparently leveled off between 50 and 60 ksi (344.7 and 413.7 MPa). This confirms the previous maximum limit of 50 kJ/in. (1968 J/mm). Unlike the SMAW electrodes, there were no usability problems with the GMAW system.

The HAZ results for both processes show an increase in yield and tensile strength over the unaffected plate material. The SMAW weldments' HAZ yield strength is almost double the typical base metal properties. These are very high and show that the HAZ has been hardened to near its capacity. This situation, if encountered in a construction weld joint, is cause for concern because of the ductility loss that accompanies these high-strength levels. Only two of the six SMAW tensile specimens met the elongation criteria of 22 percent. All of the GMAW tensile specimens had enough ductility to meet the 22 percent elongation requirements. The SMAW specimens were significantly more porous, which affected their ductility.

Impact Test Results

Figures 6 through 11 graph the dynamic tear impact energy vs. test temperature for each weldment. Each figure gives the all-weld metal impact results and the associated HAZ impact results. The transition temperatures* for the HAZ specimens were remarkably close to those of the all-weld specimens. All the transition temperatures were lower for these high heat input welds than for the lower heat input conditions previously reported. These transition temperatures ranged from 0 to −20°C, which put them in line with the reported value of around −?°C for A36 base plate. There was no significant difference in the impact results between the SMAW and GMAW weldments.

A516 Weldments

Tensile Test Results

Figure 12 is the photomacrographs of the A516 SMAW and GMAW weldments. Since this was the same weld metal as used for the A36 weldments, the heat of welding caused grain refinement of the coarse dendrites of the weld metal. The base metal shows some grain coarsening, but not nearly as much of the A36 steel showed. The GMAW beads penetrated deeper than the SMAW beads.

Table 7 and Figure 13 present the test results for the E7018 weld metal and the A516 HAZ specimens over the respective heat inputs. Table 8 and Figure 14 present the test results for the ER70S-3 weld metal and the A516 HAZ specimens over the respective heat inputs. The minimum yield strength and ultimate tensile strength are the same for both the SMAW and the GMAW electrodes: 60 ksi (413.7 MPa) minimum yield strength and 72 ksi (496.4 MPa) minimum tensile strength.

*Note: For this study, the transition temperature was computed as the knee of the dynamic tear curve at the lower shelf.

As the heat input increases from 60 to 90 kJ/in. (2362 to 3543 J/mm), the yield strength of the SMAW weld metal decreases to just above the minimum strength level permitted. Also, the span between the two specimens decreases as the heat input increases. The tensile strength was satisfactory; the lowest value was 73.6 ksi (507.5 MPa). The HAZ yield and tensile strength results show the same trends as the all-weld specimens, with the strength decreasing as the heat input increased. In no case did the HAZ yield strength fall below the 38 ksi (262.0 MPa) minimum for the A516 Grade 70 plate. The tensile strength also did not go below the 70 ksi (482.6 MPa) minimum for the base plate.

The tensile results of the GMAW weldments shown in Figure 14 show that the yield strength of the all-weld metal specimens is at or below the minimum requirements of 60 ksi (413.7 MPa) for all heat inputs. The ultimate tensile strengths of the all-weld specimens decline with increasing heat input. The values for the highest heat input were below the 72 ksi (496.4 MPa) minimum for the ER70S-3 filler metal. The results of the HAZ test specimens are within the specification limits for the A516 Grade 70 plate material. Only one of the SMAW tensile specimens had less elongation than required for the E7018 electrode (22 percent). All others exceeded the requirements. As with the A36 steel weldments, the GMAW tensile specimens all exceeded the 22 percent elongation requirements. There was somewhat less porosity in the A516 and E7018 weldments than in the A36 and E7018 weldments but it was still considered a problem along with the fluidity of the slag.

Impact Test Results

Figures 15 through 20 graph for each weldment the dynamic tear impact energy absorbed vs. test temperature for the range of heat inputs investigated. Each figure gives the all-weld metal impact results and the associated HAZ impact results. The transition temperatures for the HAZ specimens were mostly higher than the all-weld metal specimens, although the transition temperatures were on a par with the high heat input end of previously reported data. These transitions ranged from +15 to −20°C. This temperature range brackets the transition temperature of the base plate (around −5°C). There is no significant difference between the impact results for the SMAW and GMAW processes at this high heat input.

A514 Weldments

Tensile Test Results

Figure 21 shows the photomacrographs of the SMAW and GMAW weldments in the A514 steel. The SMAW weldment has two pockets of slag and the GMAW weldment has an area of poor penetration and fusion. The heat of welding had less effect on the previous weld bead than for the other weldments. There was very little grain refinement of the coarse dendrites and minimal grain coarsening in the base metal.

Table 9 and Figure 22 present the test results for the E11018 weld metal and the A514 HAZ specimens over the respective heat inputs. Table 10 and Figure 23 present the test results for the ER120S-1 weld metal and the A514 HAZ specimens over the respective heat inputs.

The yield strength of the SMAW weldments drops off as the heat input increases. All the welds meet the minimum requirements for yield strength of 97 ksi (668.8 MPa). All but two of the specimens met the 110 ksi (758.4 MPa) minimum tensile strength requirement. The two that did not meet the requirement had heavy porosity that also interfered with the ductility as shown by the low elongation and reduction-in-area measurements. The minimum of 15 percent elongation was met by only two of the tensile bars.

The yield strength of the GMAW weldments fell below the 105 ksi (723.7 MPa) minimum for all but two of the specimens. The material microstructure apparently changed from a martensitic to pearlitic bainitic microstructure; thus, the previous maximum of 50 kJ/in. (1968 J/mm) heat input should remain. The difference between the GMAW and the SMAW tensile strength results probably lies in the difference in the chemical make-up of the two systems.

Impact Results

Figures 24 through 29 graph the dynamic tear impact energy vs. test temperature for each weldment. The figures give the all-weld metal impact results and the associated HAZ impact results. The impact energy at a given temperature for the HAZ specimens is lower than that for the all-weld specimens. The transition temperature for the weld metal is at or below −20°C, while the transition for the HAZ is not well defined. The values for the impact specimens all appear to be on the lower shelf out to +60°C. This is in contrast to the unaffected base plate results reported earlier that had a transition of -60°C.

General

This work has confirmed the previous limits for each material and electrode used in the investigation. The usability of the SMAW electrodes became a large concern as the heat input was increased. The molten slag had high fluidity that allowed it to run everywhere, making slag entrapment a problem. The SMAW work also produced large quantities of porosity that caused the ductility to fall off. These usability concerns are the limiting factors for the heat input.

The GMAW electrodes did not have the same usability problems. Because of the chemical differences between the SMAW and GMAW electrodes, the strength level of the GMAW weldments decreased with increasing heat input until, at some point, the strength was below the minimum requirement. This was true for the ER70S-3 electrode. Because of different transformation products, the ER120S-1 electrode strength levels fell below the minimum at heat inputs above 50 kJ/in. (1968 J/mm).

There were no observed trends in the impact results for any of the weldments produced for this series or when compared to the previous work.

4 CONCLUSIONS AND RECOMMENDATIONS

For each of the materials investigated, the effects of increased heat input are generally to reduce the strength levels but not to affect the impact properties.

1. The A36 steel weldments with E7018 SMAW electrode were limited to 55 kJ/in. (2165 J/mm) by usability problems with fluid sag and porosity, even though the strength was satisfactory.

2. The A36 steel weldments with ER70S-1 GMAW electrode were limited to 50 kJ/in. (1968 J/mm) by the minimum yield strength requirements for the electrode material.

3. The A516 steel weldments with E7018 SMAW electrode were limited to 50 kJ/in. (1968 J/mm) by the usability of the electrode with fluid sag and by porosity.

4. The A516 steel weldments with ER70S-1 GMAW electrode were limited to 50 kJ/in. (1968 J/mm) by the minimum yield strength requirements for the electrode material.

5. The A514 steel weldments with E11018 SMAW electrode were limited to 55 kJ/in. (2165 J/mm) by the usability of the electrode with fluid sag at these high heat inputs and by porosity.

6. The A514 steel weldments with ER120S GMAW electrode were limited to 50 kJ/in. (1968 J/mm) by the mimimum yield strength requirements for the electrode material.

Based on these results, it is recommended that the heat input limits given in Table 11 be used for the steels and electrodes described in this report.

Table 1
Plate and Welding Electrode Materials Used

ASTM No.	Plate Material Thickness, in. (mm)	Electrode	Diameter, in. (mm)
A36	3/4 (19)	E7018	1/8 (3.2)
		ER70S-3	1/16 (1.6)
A516, Grade 70	1(25.4)	E7018	1/8 (3.2)
		ER70S-3	1/16 (1.6)
A514	3/4 (19)	E11018	1/8 (3.2)
		ER120S-1	1/16 (1.6)

Table 2
As-Received Tensile Properties of the ASTM-Specified Plate Material Used

Plate Type	Yield Strength, ksi (MPa)	Ultimate Tensile Strength, ksi (MPa)	Elongation %	Reduction in Area %
A36	35.6 (245.5)	70.5 (486.1)	34.8	54.0
	34.8 (239.9)	70.0 (482.6)	33.8	60.7
Specification	36 minimum (248.2)	58-80 (399.9-551.6)	23 minimum	Not specified
A516, Grade 70	39.9 (275.1)	74.8 (515.7)	33.0	54.5
	40.5 (279.2)	75.2 (518.5)	30.9	53.9
Specification	38 minimum (262)	70-90 (482.6-620.5)	21 minimum	Not specified
A514	121.3 (836.3)	124.7 (859.8)	20.9	69.1
	121.3 (836.3)	124.3 (857.0)	21.1	70.1
Specification	100 minimum (689.5)	110-130 (758.4-896.3)	18 minimum	40 minimum

Table 3
AWS Specification Table Property Requirements for Electrodes

Electrode	Specification	Yield Strength, ksi (MPa)	Ultimate Tensile Strength, ksi (MPa)	Elongation %
E7018	A5.1-69	60 (413.7)	72 (496.4)	22
E11018	A5.5-69	97 (668.8)	110 (758.4)	15
ER70S-3	A5.18-69	60 (413.7)	72 (496.4)	22
ER120S-1	A5.28-79	105-122 (724.0-841.2)	120 (827.4)	14

Table 4
Welding Variables Used to Produce the High Heat Input Weldments

SMAW

Weldment Specimen Identification	Voltage	Current	Travel Speed	Heat Input J/in. (J/mm)
A36 Steel, 3/4 in. (19 mm) Thick				
AM	28	165	4.6	60,260 (2372)
AQ	28	165	3.7	74,919 (2950)
AT	28	165	3.1	89,419 (3520)
A516 Steel, 1 in. (25 mm) Thick				
AN	28	165	4.6	60,260 (2372)
AR	28	165	3.7	74,919 (2950)
AJ	28	165	3.1	89,419 (3520)
A514 Steel, 3/4 in. (19 mm) Thick				
AL	28	165	4.7	58,979 (2322)
AP	28	165	3.7	74,919 (2950)
AU	28	165	3.1	89,419 (3520)

Table 4 (Cont'd)

GMAW

Weldment Specimen Identification	Voltage	Current	Travel Speed	Heat Input J/in. (J/mm)
		A36 Steel, 3/4 in. (19 mm) Thick		
AJ	32	360	9.2	75,130 (2958)
AK	32	360	7.1	89,766 (3534)
AG	32	340	7.7	91,944 (3620)
		A516 Steel, 1 in. (25 mm) Thick		
AD	33	360	11.0	64,800 (2551)
AE	32	370	8.9	79,820 (3142)
AF	32	350	7.0	96,000 (3779)
		A514 Steel, 3/4 in. (19 mm) Thick		
AH	27	460	12.6	59,143 (2328)
AC	30	440	10.9	72,660 (2860)
AB	30	430	7.2	107,500 (4232)

Table 5
Tensile Test Results–A36 Steel SMAW

Weldment Specimen Identification	Welding Heat Input J/in. (J/mm)	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	Elongation %	Reduction in Area %
		All-Weld Specimens			
AM	60,260 (2372)	86.4 (595.7)	86.4 (595.7)	7.3	26.5
		62.0 (422.5)	70.0 (482.6)	10.1	28.5
AQ	74,919 (2950)	63.0 (434.4)	75.0 (517.1)	20.0	43.1
		69.0 (475.7)	80.0 (551.6)	22.4	70.9
AT	89,419 (3520)	72.0 (496.4)	86.0 (593.0)	27.0	67.3
		60.6 (417.8)	67.2 (463.0)	11.0	19.1
		HAZ Specimens			
AM	60,260 (2372)	71.0 (489.5)	96.0 (661.9)	23.6	53.9
AQ	74,919 (2950)	66.0 (455.0)	94.0 (648.1)	24.0	52.3
AT	89,419 (3520)	71.0 (489.5)	100.6 (693.6)	20.9	50.9

Table 6
Tensile Test Results–A36 Steel GMAW

Weldment Specimen Identification	Welding Heat Input J/in. (J/mm)	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	Elongation %	Reduction in Area %
		All-Weld Specimens			
AJ	75,130 (2458)	60.2 (415.1)	76.2 (525.4)	26.2	63.6
		56.1 (386.8)	72.2 (497.8)	26.4	61.6
AK	89,766 (3534)	58.1 (400.6)	76.2 (525.4)	28.2	44.9
		52.1 (359.2)	70.2 (484.0)	34.5	61.6
AG	91,944 (2958)	53.1 (366.1)	68.2 (470.2)	28.9	49.5
		52.1 (359.2)	62.2 (428.8)	32.3	64.0
		HAZ Specimens			
AJ	75,130 (2958)	54.1 (373.0)	80.2 (552.0)	27.2	48.9
AK	89,766 (3534)	57.1 (393.7)	79.2 (546.1)	32.0	51.7
AG	91,944 (2958)	75.1 (517.8)	80.2 (553.0)	31.2	58.1

Table 7
Tensile Test Results–A516 Steel SMAW

Weldment Specimen Identification	Welding Heat Input J/in. (J/mm)	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	Elongation %	Reduction in Area %
		All-Weld Specimens			
AN	60,260 (2372)	74.0 (510.2)	84.0 (579.2)	24.1	68.2
		63.2 (435.8)	77.0 (530.9)	27.1	71.7
AR	74,919 (2950)	70.0 (482.6)	80.6 (555.7)	18.5	46.7
		62.0 (427.5)	73.6 (507.5)	29.7	73.0
AS	89,419 (3520)	66.0 (455.1)	78.0 (537.8)	27.0	71.7
		61.2 (422.0)	76.0 (524.0)	23.8	62.2
		HAZ Specimen			
AN	60,260 (2372)	66.0 (455.1)	83.0 (527.3)	25.6	67.8
AR	74,919 (2950)	64.0 (441.3)	81.8 (564.0)	28.8	69.1
AS	89,419 (3520)	63.2 (435.8)	80.4 (554.3)	27.2	70.9

Table 8
Tensile Test Results–A516 Steel GMAW

Weldment Specimen Identification	Welding Heat Input J/in. (J/mm)	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	Elongation %	Reduction in Area %
		All-Weld Specimens			
AD	64,800 (2551)	56.1 (386.8)	72.1 (497.1)	27.4	44.3
		56.1 (386.8)	72.2 (497.8)	28.8	43.1
AE	79,820 (3142)	60.1 (414.4)	75.2 (518.5)	26.0	65.5
		56.1 (386.8)	70.2 (484.0)	27.5	60.6
AF	96,000 (3779)	57.1 (393.7)	69.2 (477.1)	27.2	60.6
		48.1 (331.6)	60.1 (414.4)	23.6	64.0
		HAZ Specimens			
AD	64,800 (2551)	62.2 (428.8)	80.2 (553.0)	24.7	50.1
AE	79,820 (3142)	56.1 (386.8)	71.0 (489.5)	27.4	56.6
AF	96,000 (3779)	56.1 (386.8)	77.2 (532.3)	29.6	57.6

Table 9
Tensile Test Results–A514 Steel SMAW

Weldment Specimen Identification	Welding Heat Input J/in. (J/mm)	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	Elongation %	Reduction in Area %
		All-Weld Specimens			
AL	58,979 (2322)	108.6 (748.6)	108.6 (748.6)	6.0	24.9
		108.0 (744.6)	126.0 (868.7)	18.5	63.6
AP	74,919 (2950)	100.6 (693.6)	116.6 (803.9)	10.5	31.2
		108.0 (744.6)	113.0 (779.1)	12.0	4.7
AU	89,419 (3520)	98.2 (677.1)	107.6 (741.9)	7.6	21.0
		102.0 (703.3)	118.8 (819.1)	20.3	59.2
		HAZ Specimens			
AL	58,979 (2322)	117.6 (810.8)	126.0 (868.7)	22.1	67.8
AP	74,919 (2950)	117.0 (806.7)	125.0 (861.8)	18.3	65.5
AU	89,419 (3520)	120.0 (827.4)	130.0 (896.3)	18.4	66.1

Table 10
Tensile Test Results - A514 Steel GMAW

Weldment Specimen Identification	Welding Heat Input J/in. (J/mm)	Yield Strength ksi (MPa)	Ultimate Tensile Strength ksi (MPa)	Elongation %	Reduction in Area %
		All-Weld Metal			
AH	59,143 (2328)	98.2 (677.1)	108.3 (746.7)	19.9	55.5
		92.2 (635.7)	109.2 (752.9)	20.4	44.9
AC	72,660 (2860)	108.3 (746.7)	117.3 (808.8)	23.5	72.6
		92.2 (635.7)	107.2 (739.1)	22.7	69.5
AB	107,500 (4232)	98.2 (677.1)	114.3 (788.1)	23.1	63.6
		100.3 (760.5)	130.3 (898.4)	17.8	62.1
		HAZ Specimen			
AH	59,643 (2328)	100.2 (690.8)	126.3 (870.8)	21.9	53.4
AC	72,660 (2860)	116.3 (801.9)	126.3 (870.8)	19.4	65.5
AB	107,500 (4232)	112.3 (774.3)	124.3 (857.0)	18.3	64.0

Table 11
Heat Input Limits for A36, A516, and A514 Steel

Steel	Electrode	Heat Input Limits kJ/in. (J/mm)
A36	E7018	20 to 55 (787.4 to 2165.4)
	E70S-3	20 to 50 (788.4 to 1968.5)
A516	E7018	20 to 50 (787.4 to 1968.5)
	E70S-3	20 to 50 (787.4 to 1968.5)
A514	E11018	20 to 55 (787.4 to 2165.4)
	E120S-1	25 to 50 (984.3 to 1968.5)

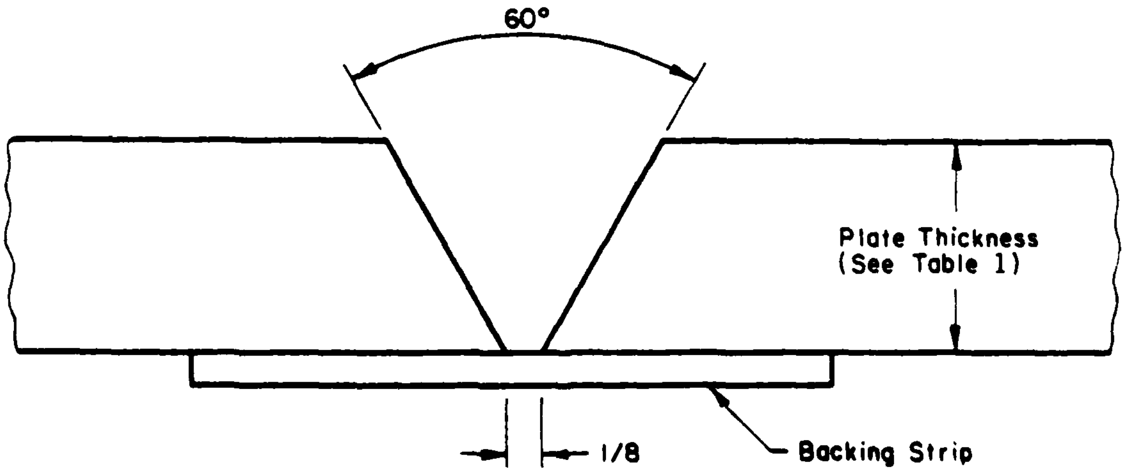
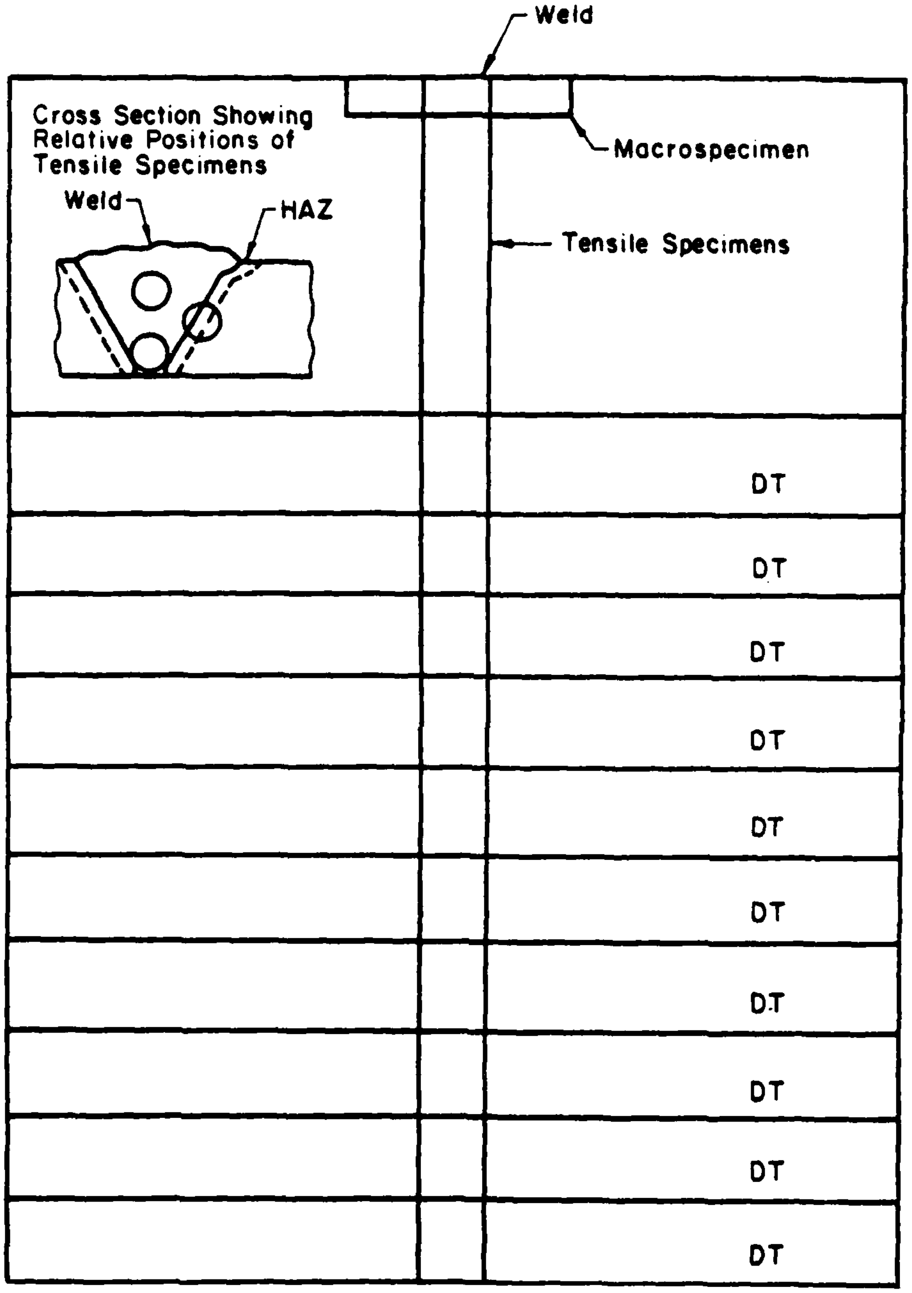


Figure 1. Joint design used for the A36, A514, and A516 steel weldments.



Note: Half of DTs Notched in Weld Metal, and Half of DTs Notched in HAZ.

Figure 2. Schematic showing specimen location as machined from weldment.

SMAW

GMAW

Figure 3. Photomacrographs of A36 steel weldments made with SMAW and GMAW processes (plate thickness 3/4 in. [19 mm]).

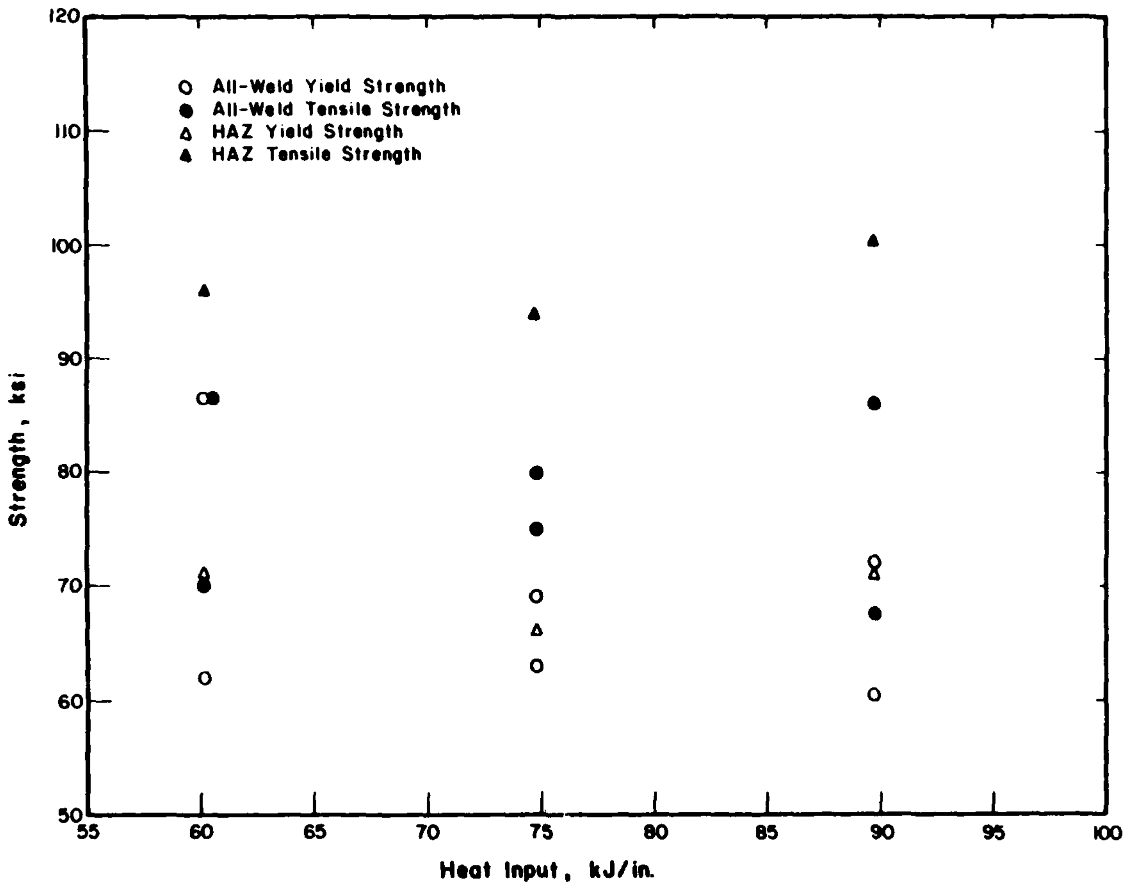


Figure 4. Tensile strength vs. heat input for A36 steel and E7018 SMAW electrode. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

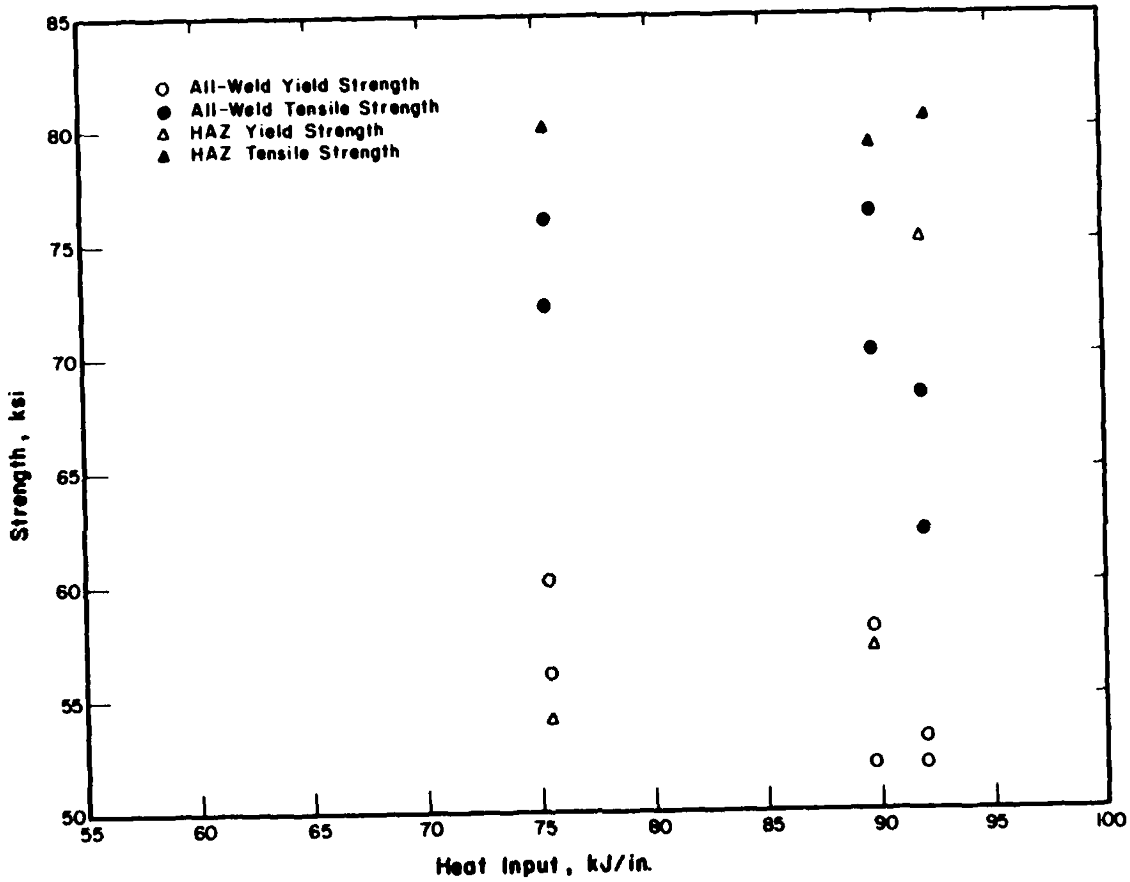


Figure 5. Tensile strength vs. heat input for A36 steel and ER70S-3 GMAW electrode. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

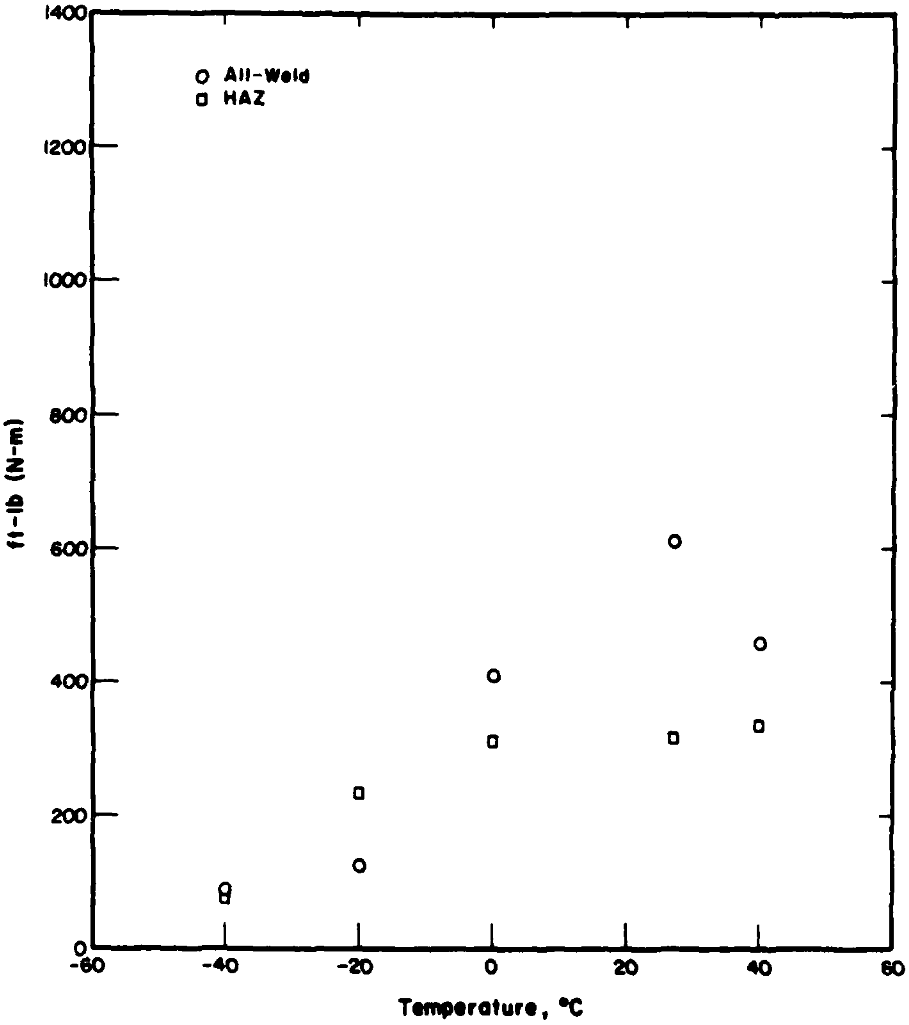


Figure 6. Dynamic tear impact energy vs. test temperature for A36 weldment AM. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

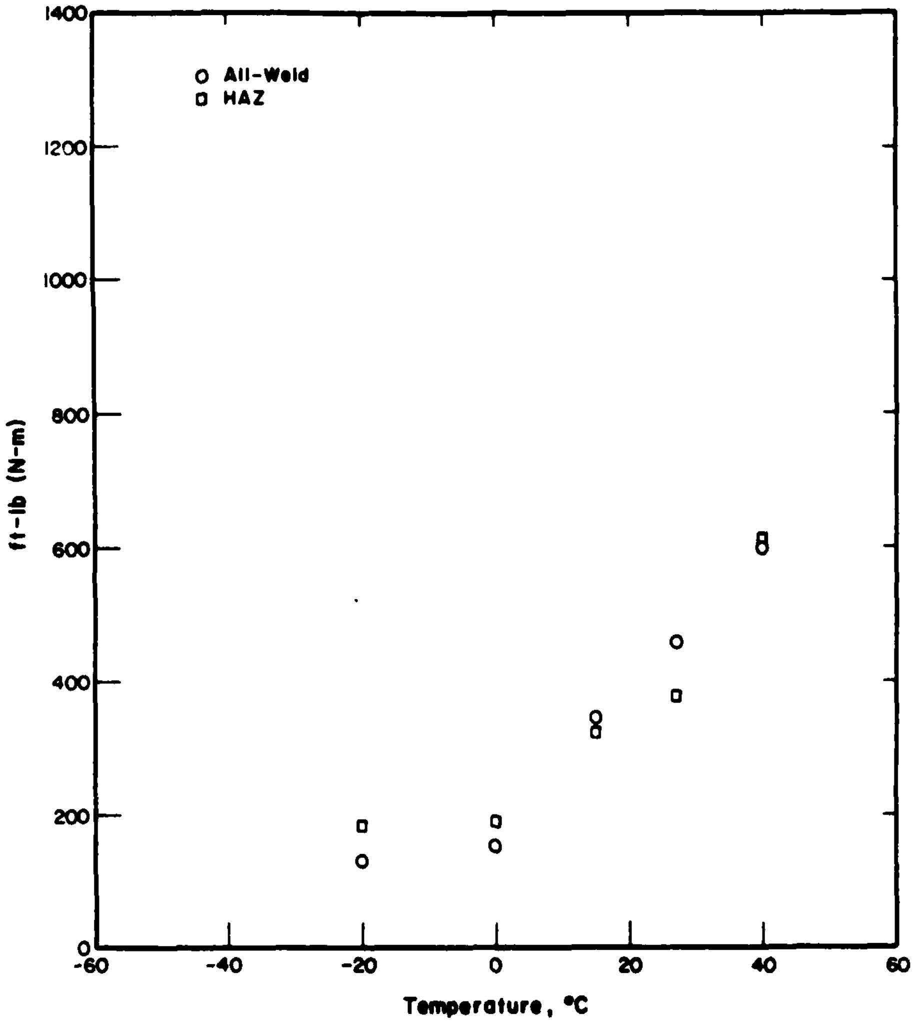


Figure 7. Dynamic tear impact energy vs. test temperature for A36 weldment AQ. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

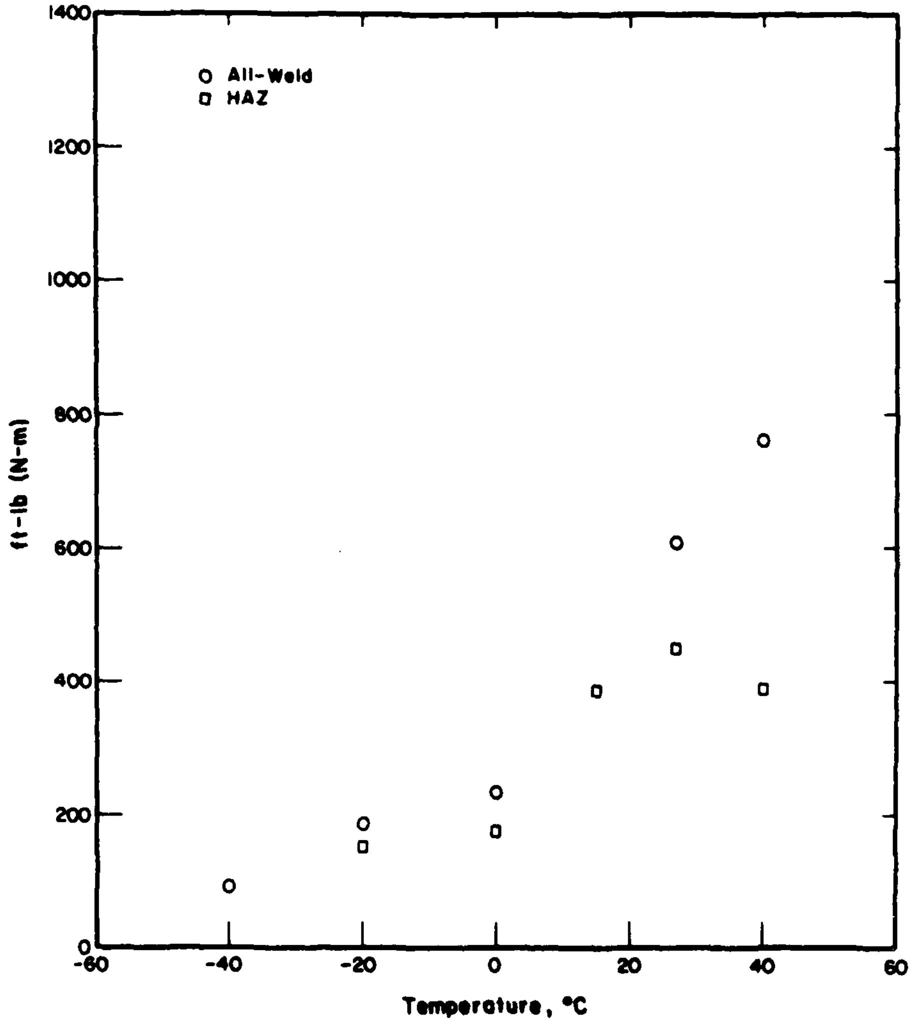


Figure 8. Dynamic tear impact energy vs. test temperature for A36 weldment AT. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

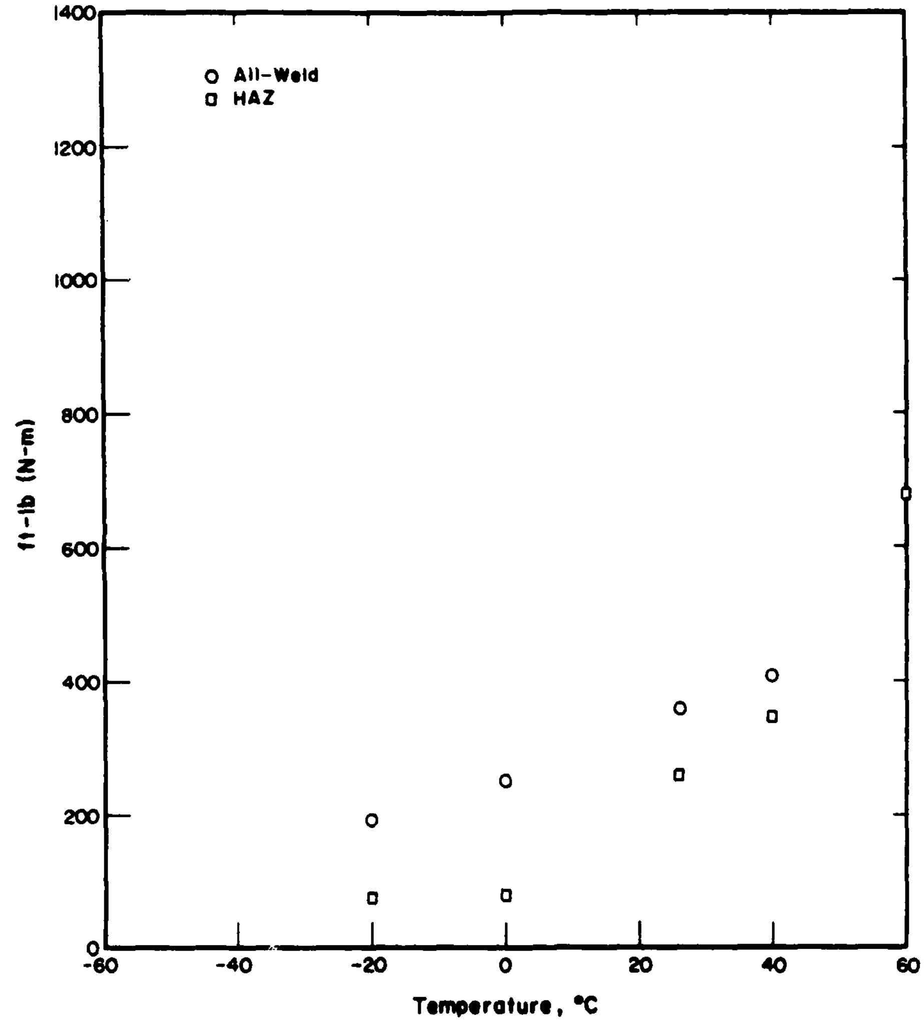


Figure 9. Dynamic tear impact energy vs. test temperature for A36 weldment AJ. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

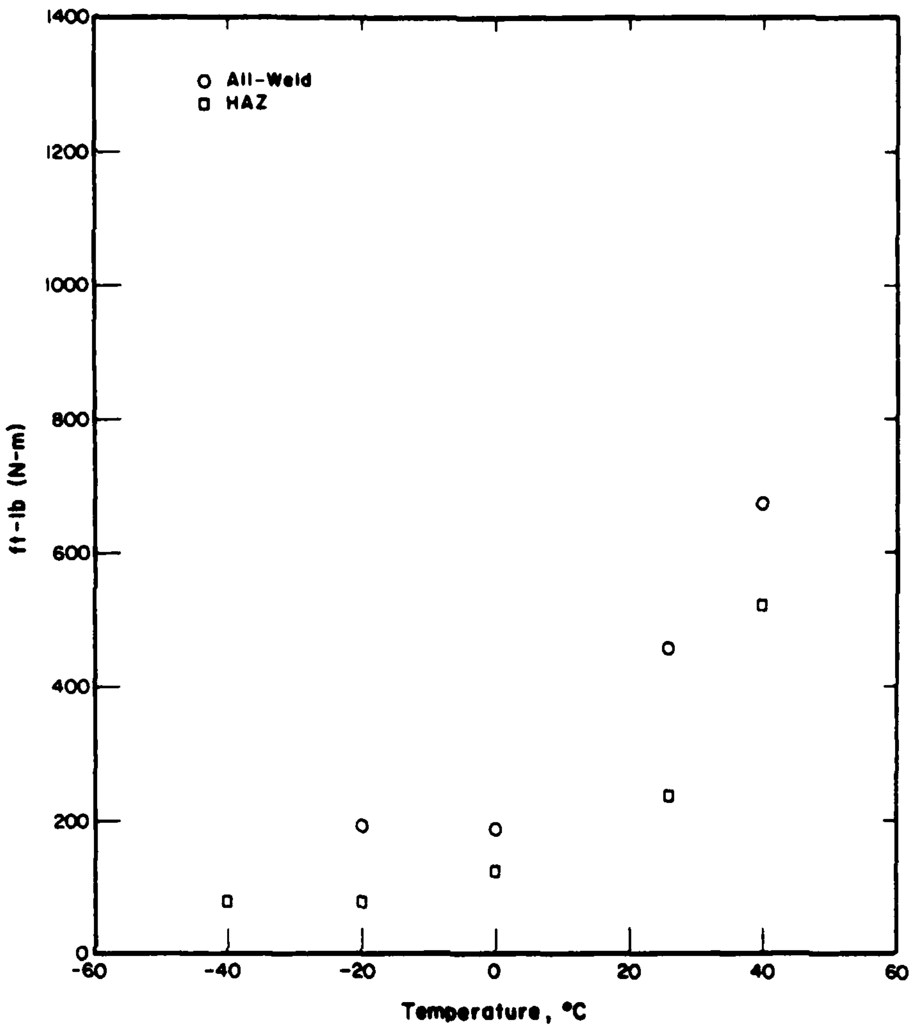


Figure 10. Dynamic tear impact energy vs. test temperature for A36 weldment AK. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

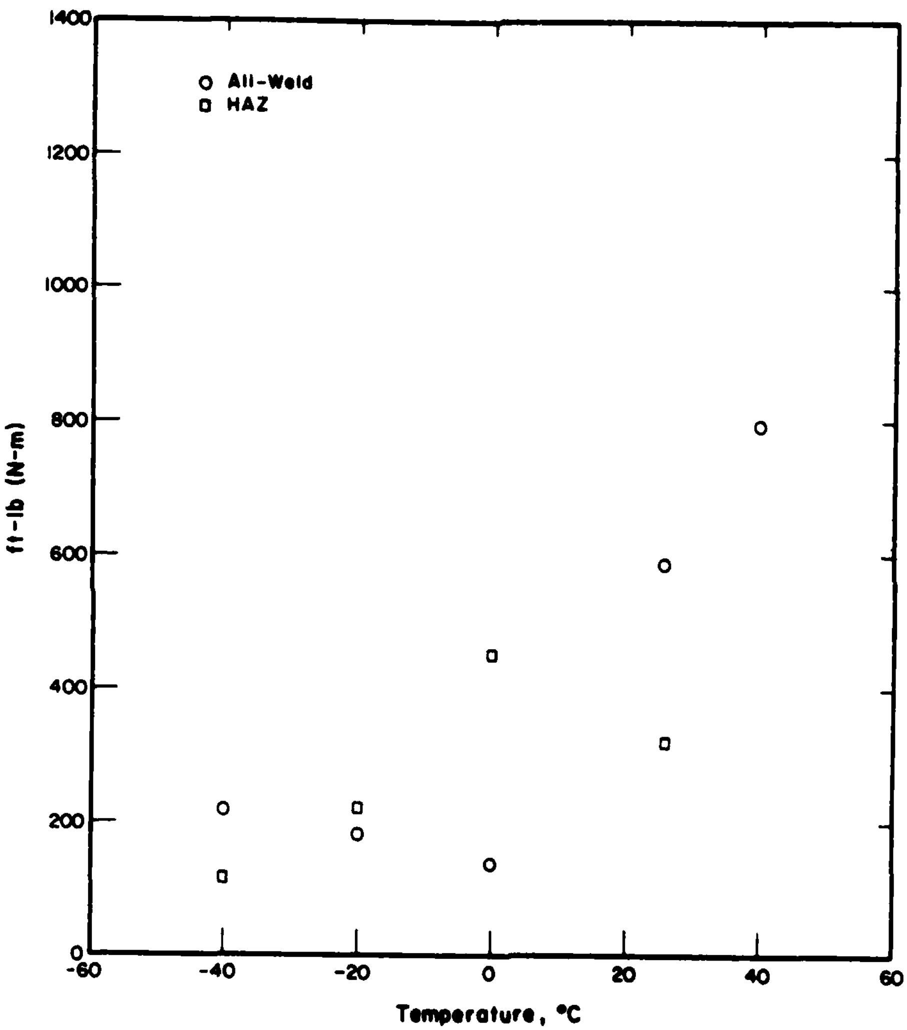


Figure 11. Dynamic tear impact energy vs. test temperature for A36 weldment AG. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

SMAW

GMAW

Figure 12. Photomacrographs of A516 weldments made with SMAW and GMAW processes (plate thickness = 1 in. [25.4 mm]). (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

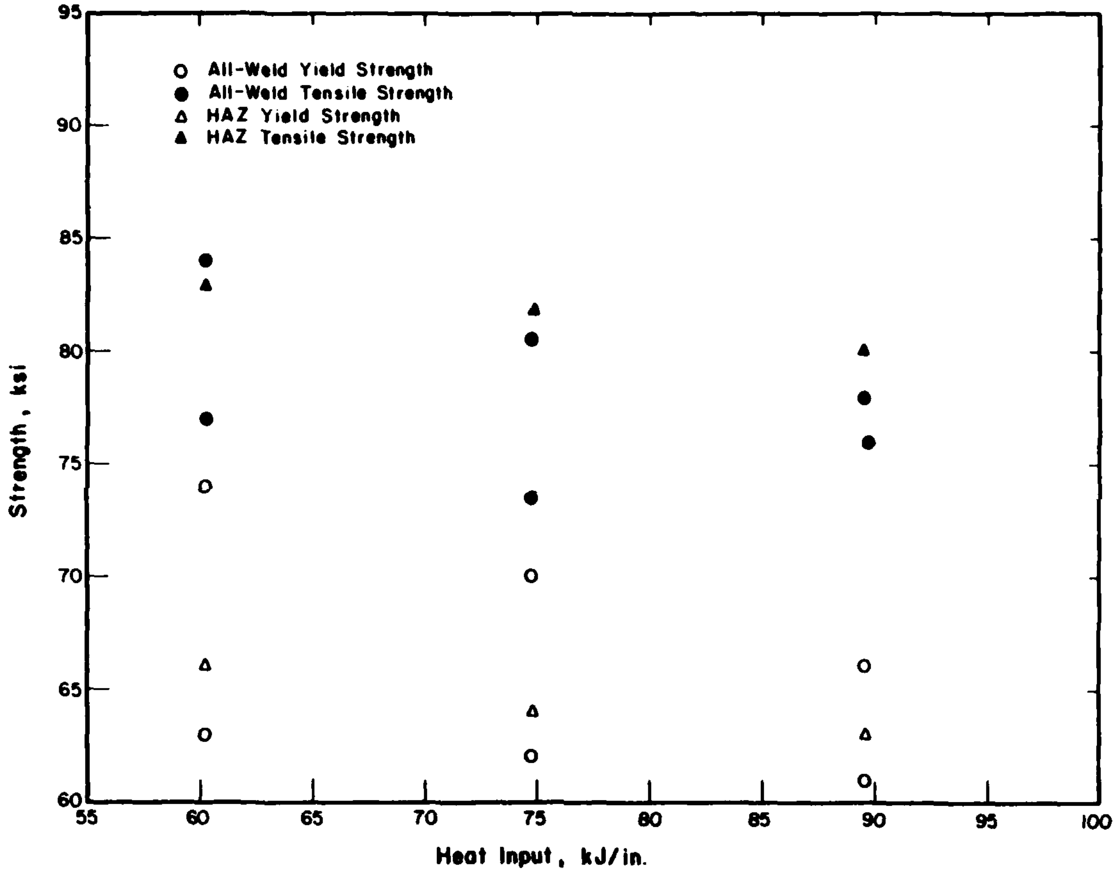


Figure 13. Tensile strength vs. heat input for A516 steel and E7018 SMAW electrode. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

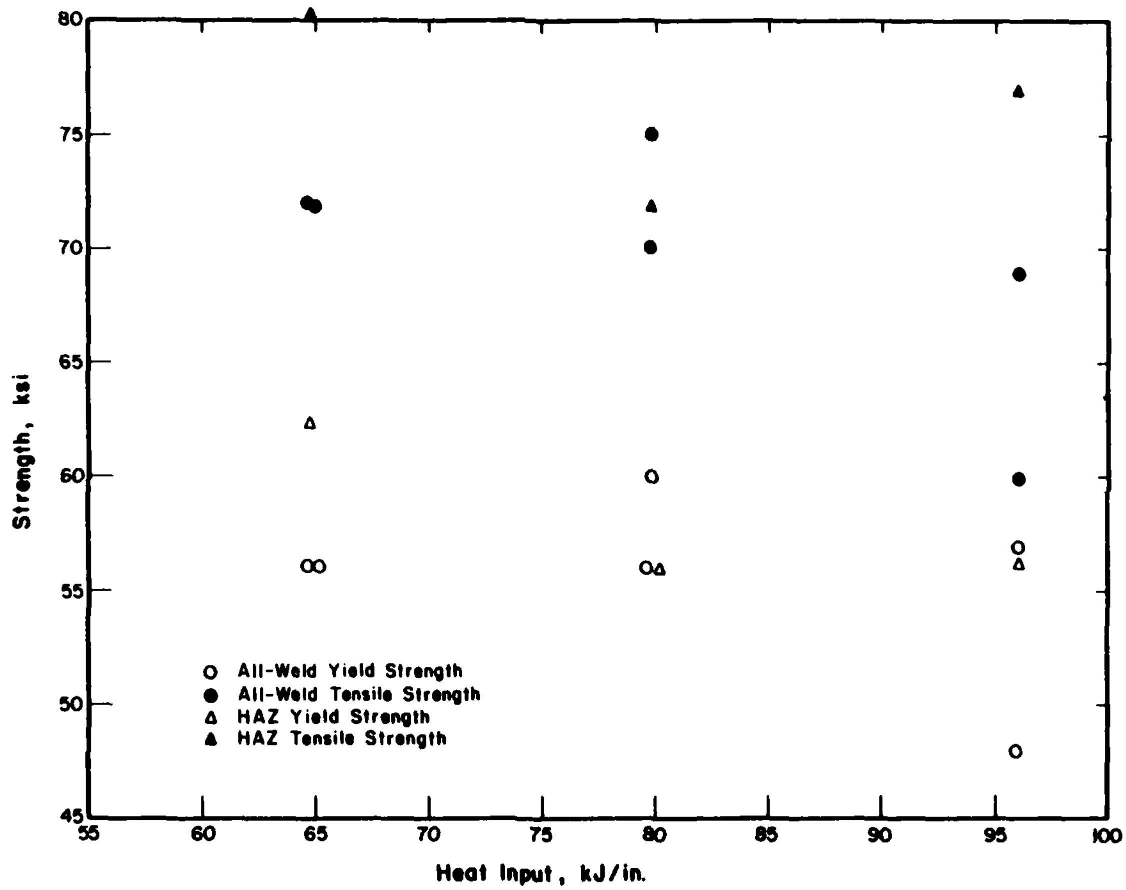


Figure 14. Tensile strength vs. heat input for A516 steel and ER70S-3 GMAW electrode. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

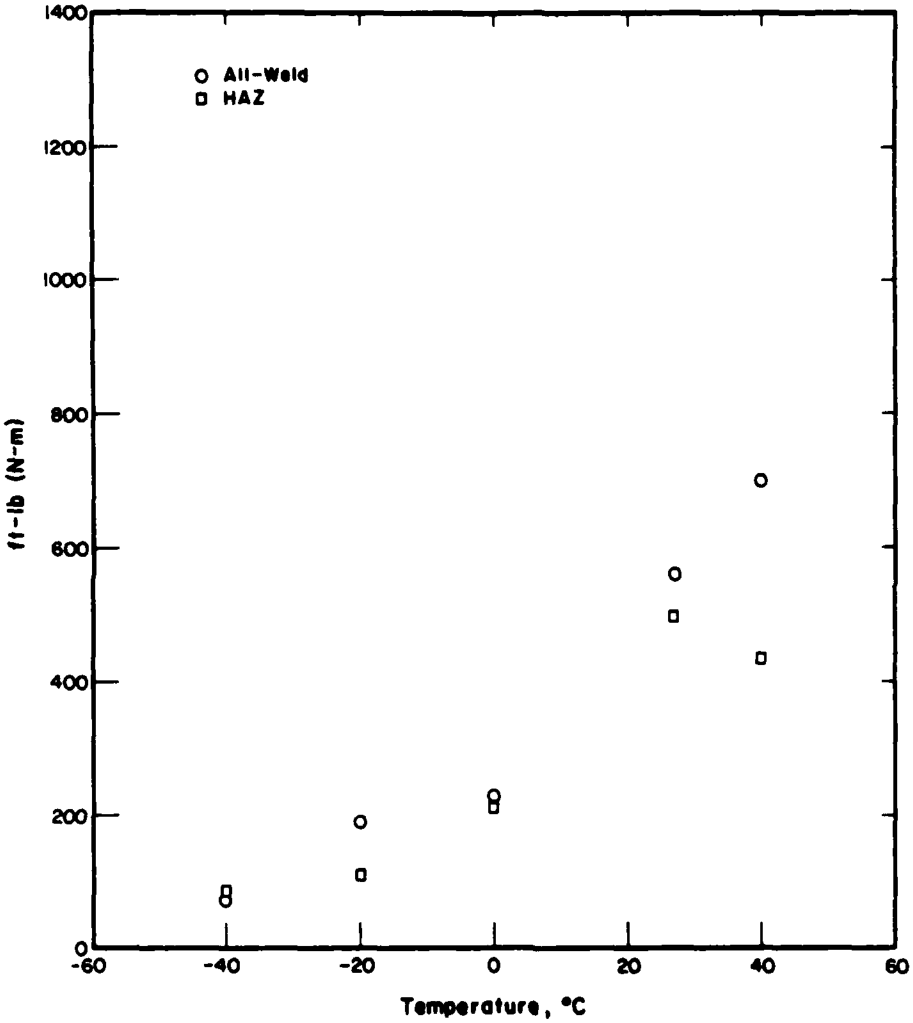


Figure 15. Dynamic tear impact energy vs. test temperature for A516 weldment AN. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

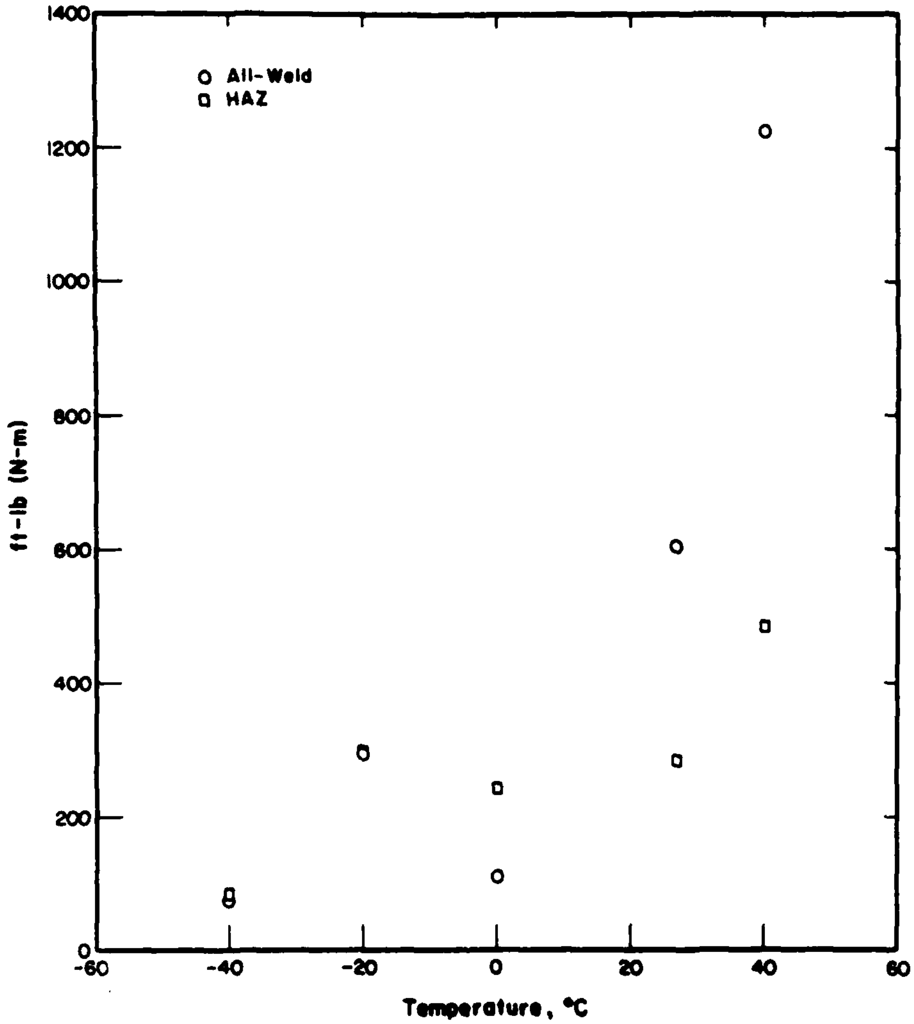


Figure 16. Dynamic tear impact energy vs. test temperature for A516 weldment AR. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

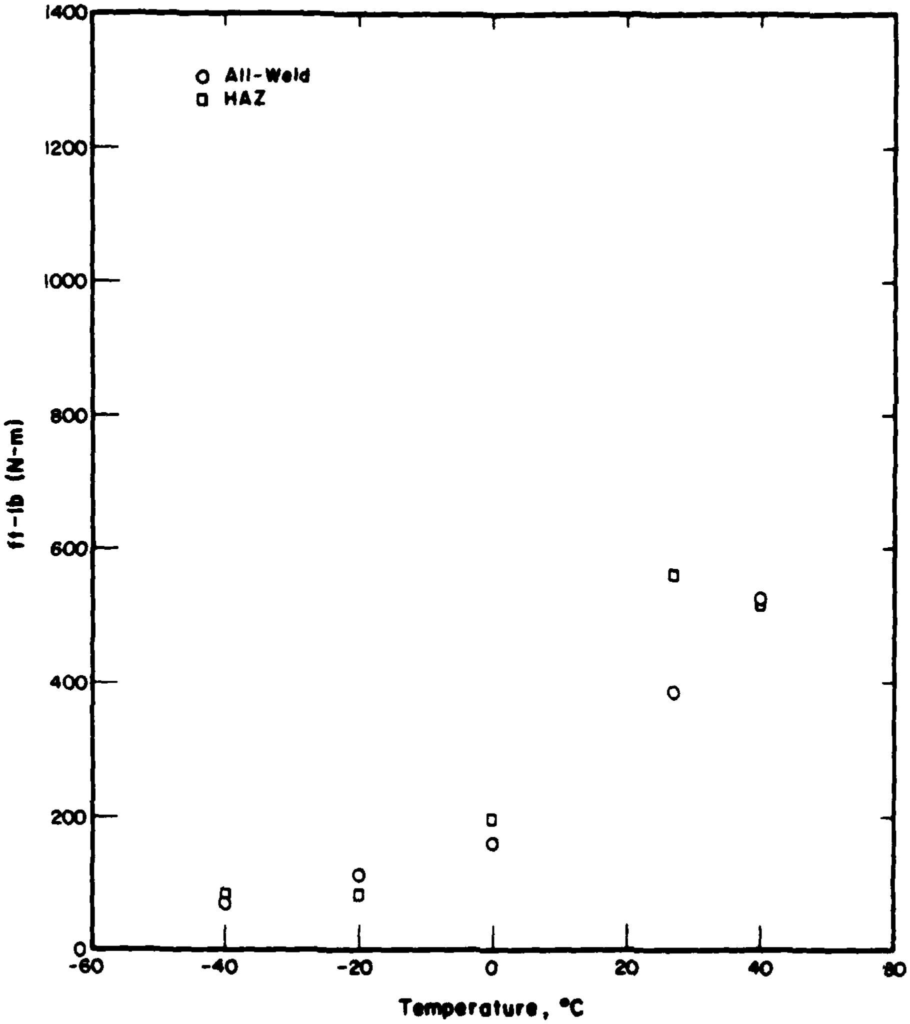


Figure 17. Dynamic tear impact energy vs. test temperature for A516 weldment AS. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

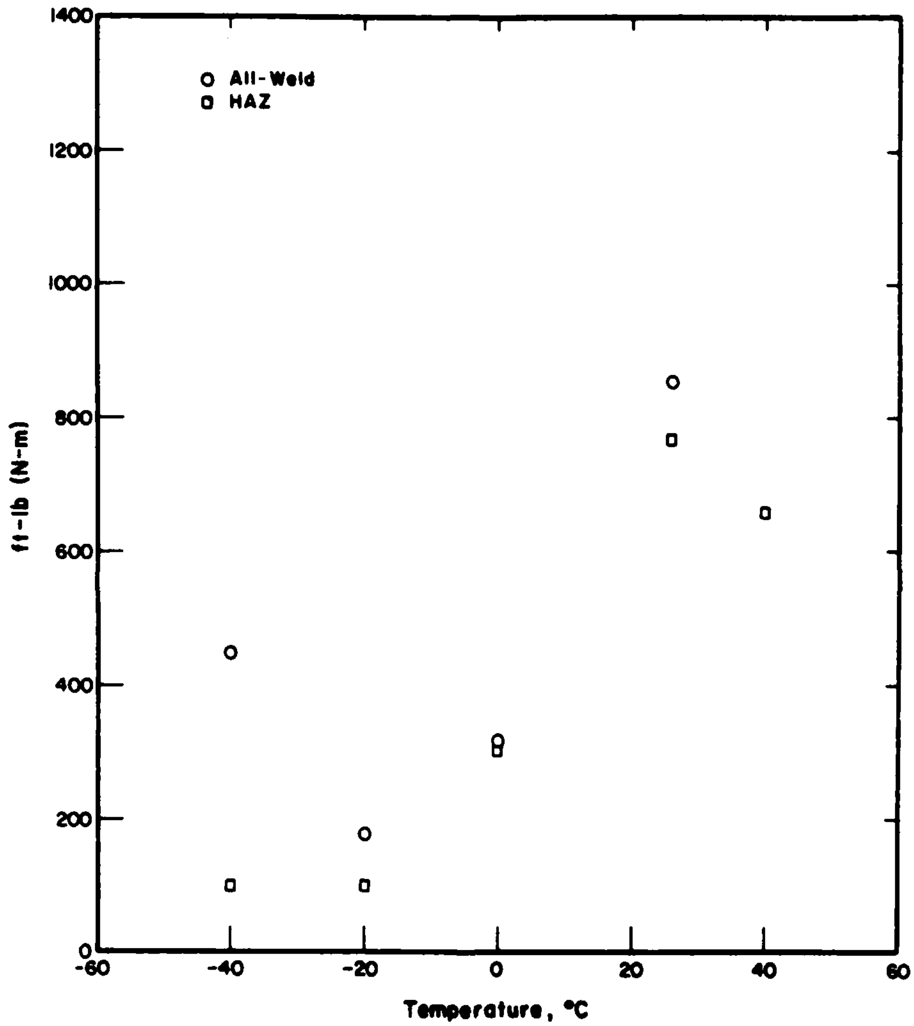


Figure 18. Dynamic tear impact energy vs. test temperature for A516 weldment AD. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

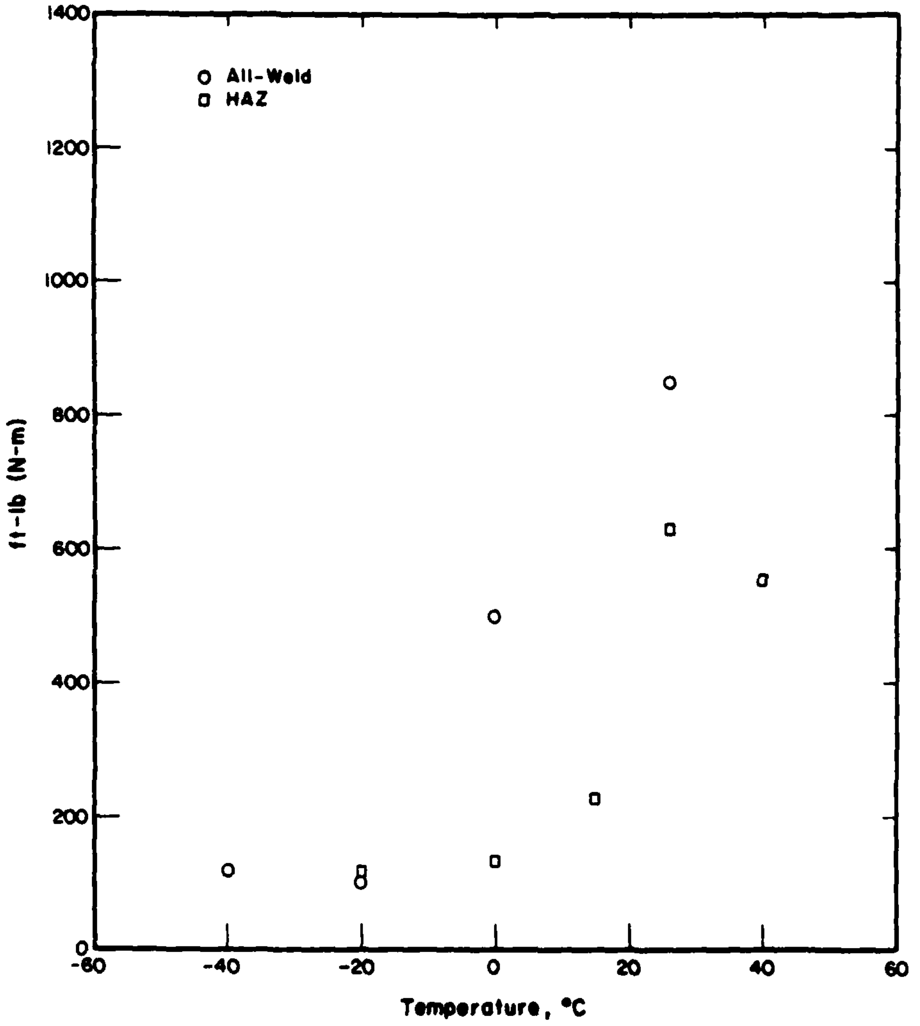


Figure 19. Dynamic tear impact energy vs. test temperature for A516 weldment AE. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

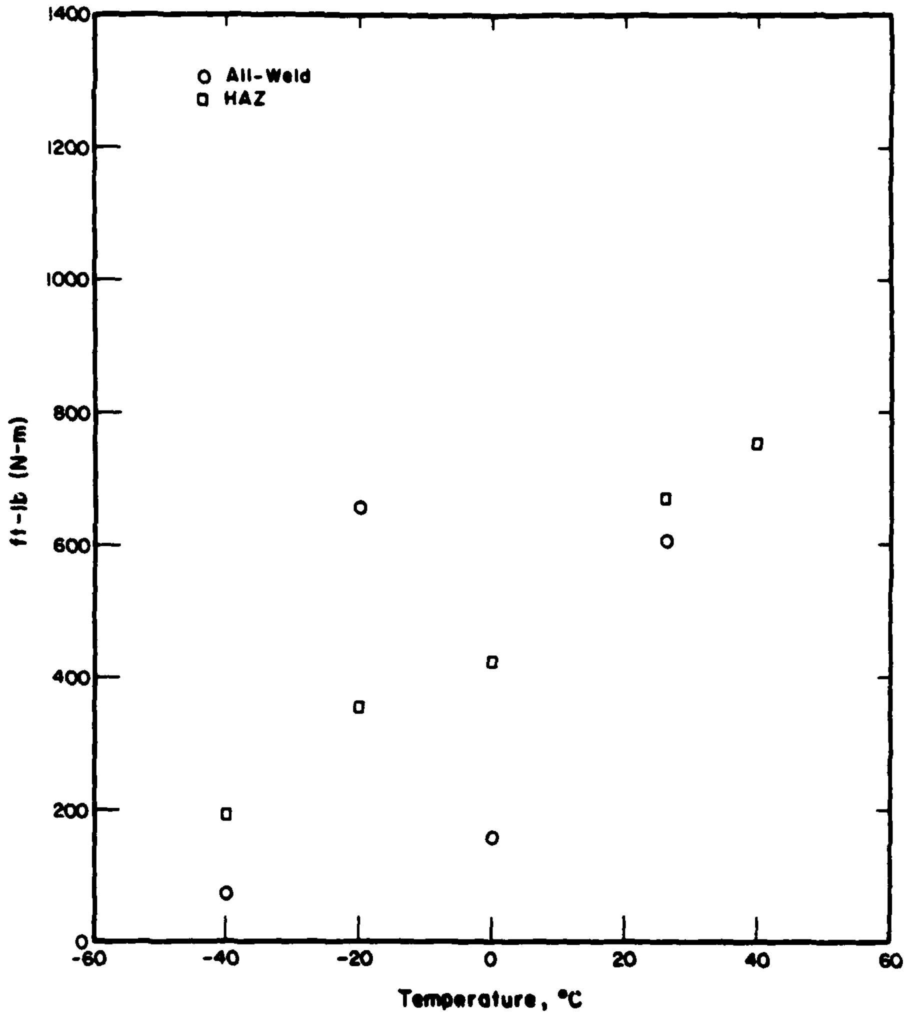
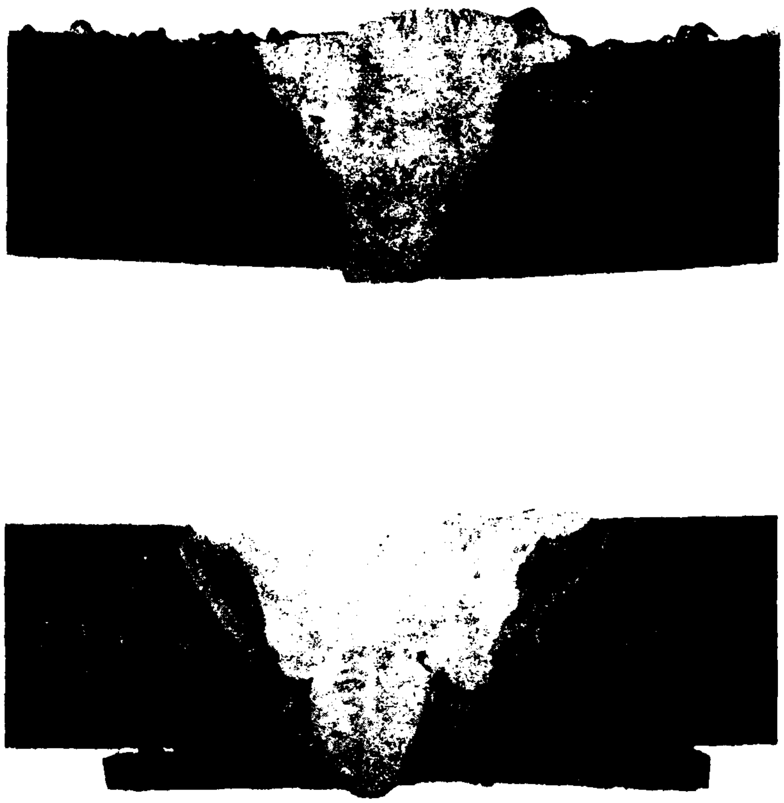


Figure 20. Dynamic tear impact energy vs. test temperature for A516 weldment AF. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)



SMAW

GMAW

Figure 21. Photomacrograph of A514 weldments made with SMAW and GMAW processes (plate thickness, 3/4 in. [19 mm]). (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

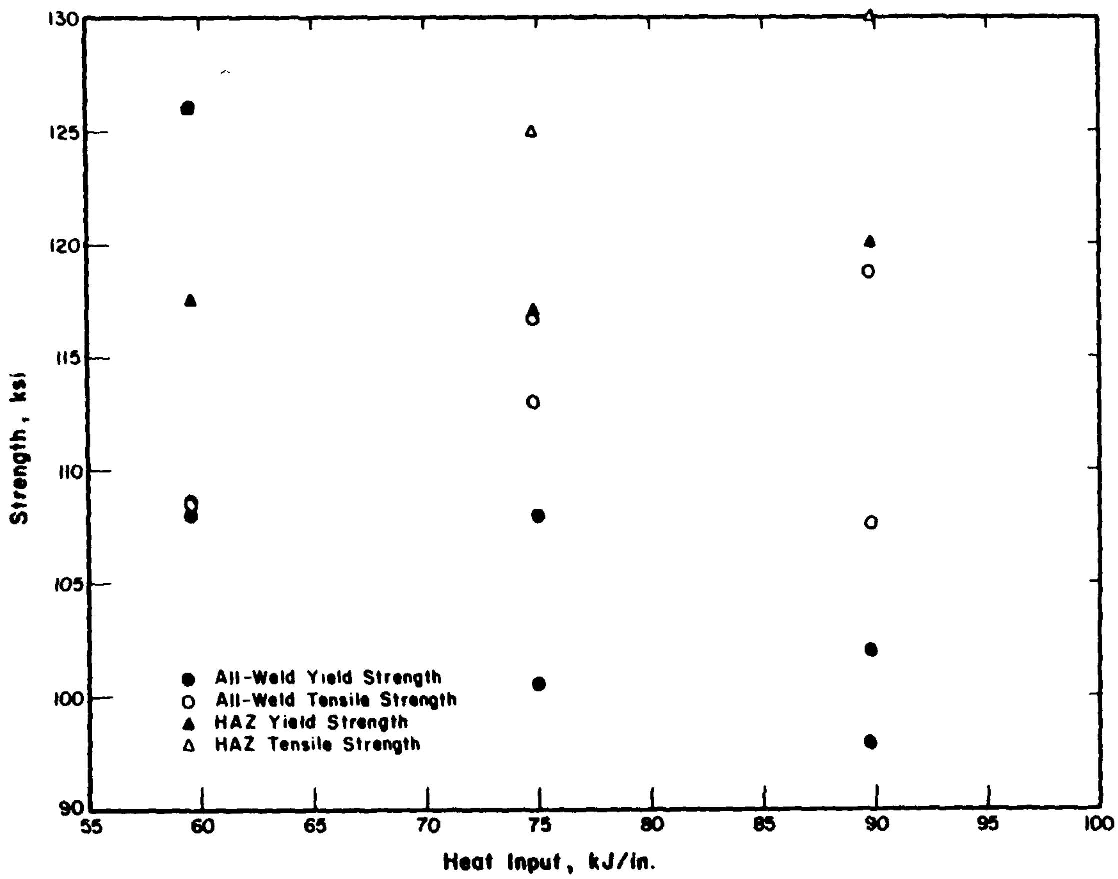


Figure 22. Tensile strength vs. heat input for A514 and E11018 SMAW electrode. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

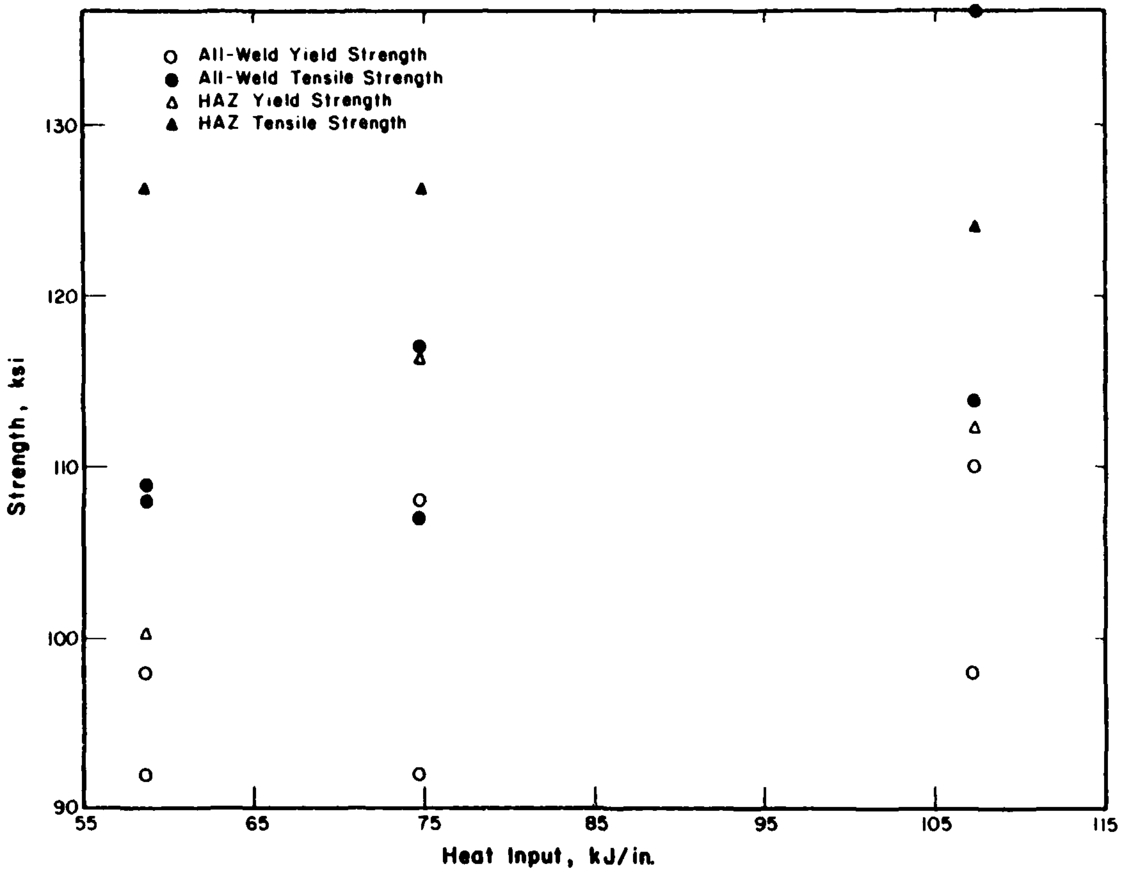


Figure 23. Tensile strength vs. heat input for A514 steel and ER120S-1 GMAW electrode. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

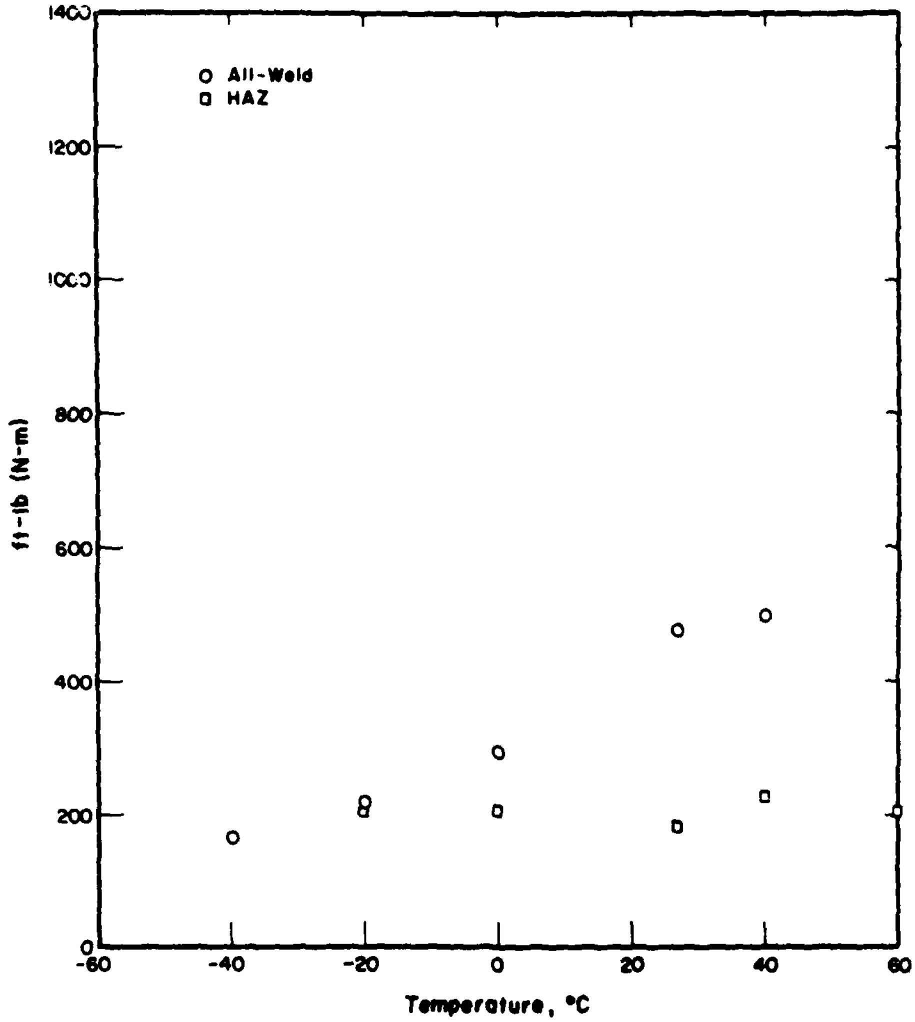


Figure 24. Dynamic tear impact energy vs. test temperature for A514 weldment AL. (Metric conversion factors. 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

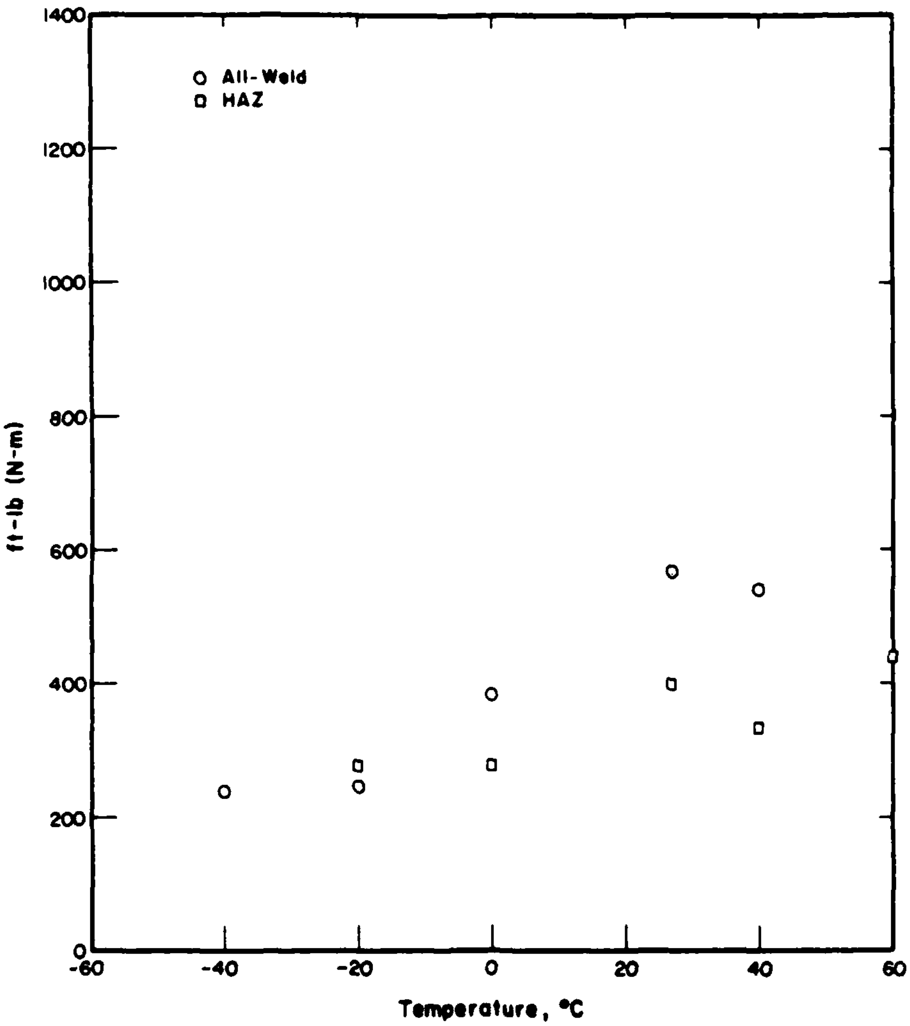


Figure 25. Dynamic tear impact energy vs. test temperature for A514 weldment AP. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

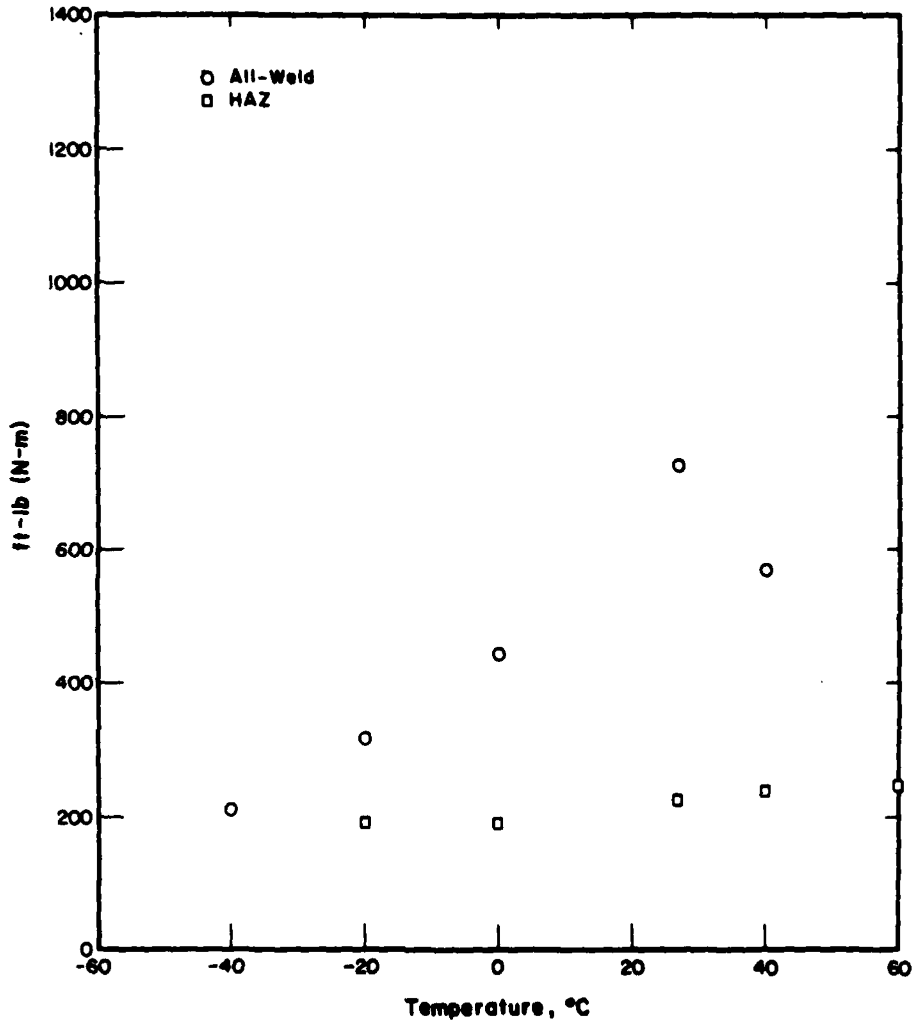


Figure 26. Dynamic tear impact energy vs. test temperature for A514 weldment AU. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

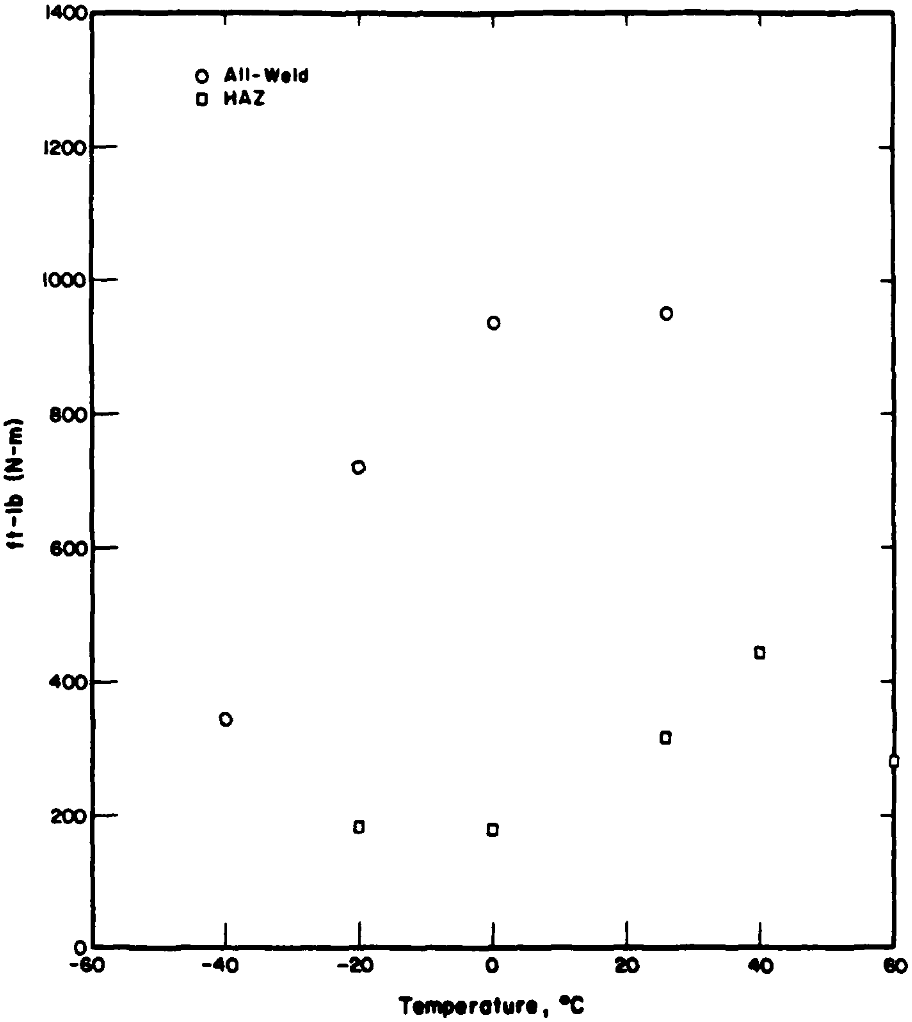


Figure 27. Dynamic tear impact energy vs. test temperature for A514 weldment AH. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

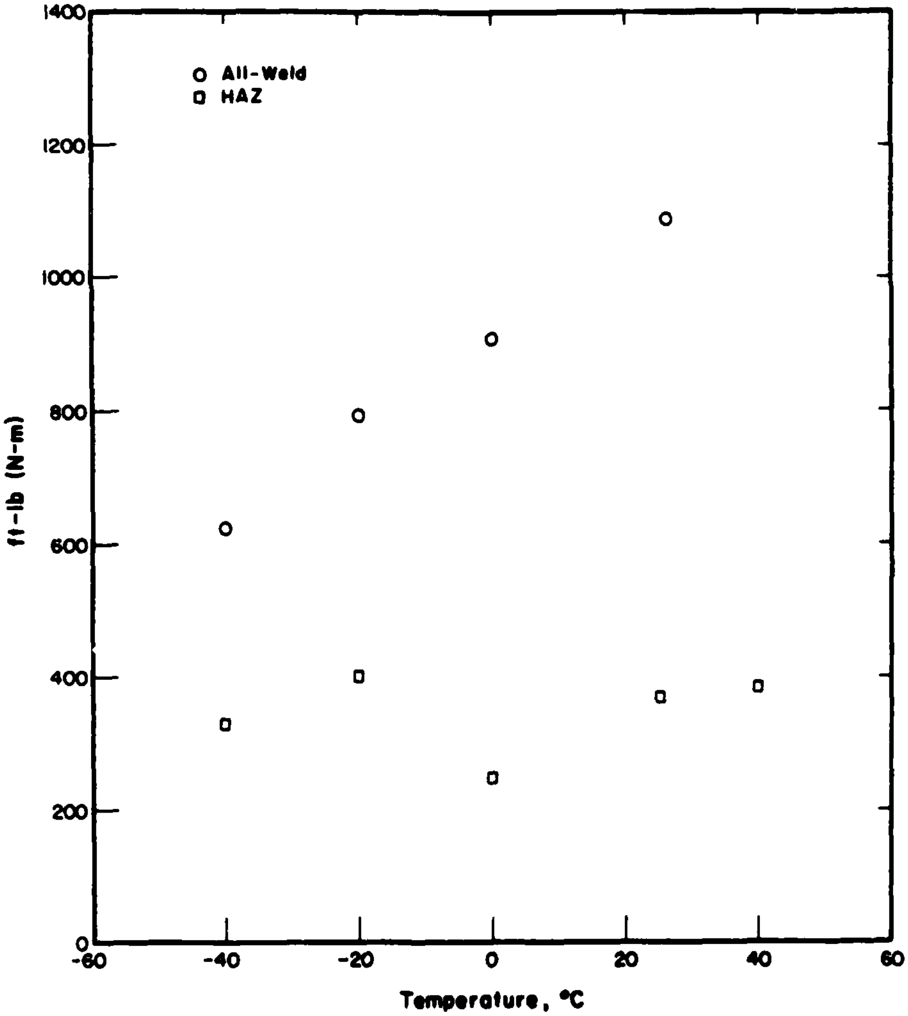


Figure 28. Dynamic tear impact energy vs. test temperature for A514 weldment AC. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

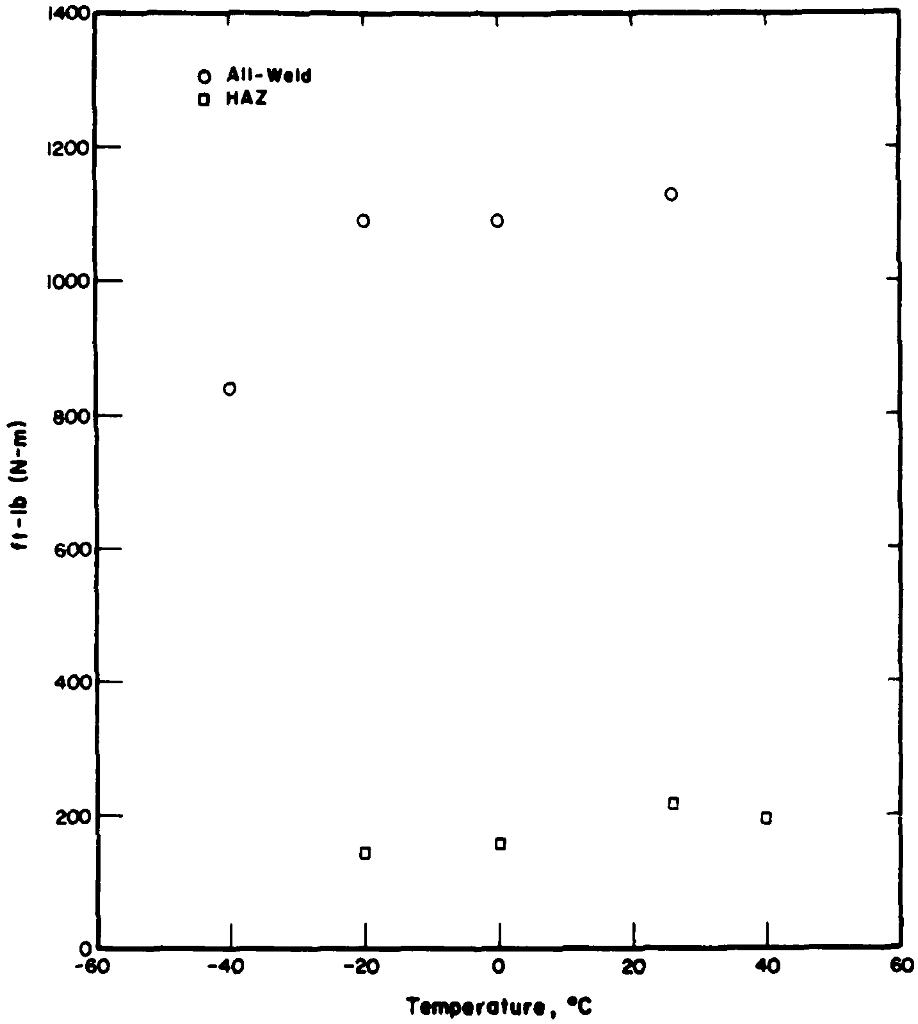


Figure 29. Dynamic tear impact energy vs. test temperature for A514 weldment AB. (Metric conversion factors: 1 ksi = 6.895 MPa; 1 kJ/in. = 39.37 J/mm.)

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